COMPARISON OF PRESSURE BUILD UP IN INJECTION WELLS USING ANALYTICAL AND NUMERICAL MODELS

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COMPARISON OF PRESSURE BUILD UP IN INJECTION WELLS USING ANALYTICAL AND NUMERICAL MODELS

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CHAPTER I

INTRODUCTION

Injection well is still being one of the most widely used method of disposal for various industrial liquid wastes. An engineering task that is often required of injection well operators and those regulating injection well operation is the prediction of the probable rate of pressure increase in the injection reservoir, resulting from a proposed injection operation. The pressure build-up is associated with any injection operation, including those of oil field brine injection, industrial wastewater injection, uranium leaching, etc. The pressure build-up in an injection well is always a concern for those who analyze the economics and the potential environmental impact of this operation.

The environmental Protection Agency (EPA) has classified the types of waste injection wells under the UIC (Underground Injection Control) Program. These classes are: class I for hazardous waste, class II for oil and gas, class III for mining, and class IV for commercial and chemical wastes. The last two classes of injection are currently banned under the UIC Program, meaning no certification for operation will be issued.

The objective of this investigation is to present a comparison of results obtained from the numerical method with the analytical method of analyzing for lateral pressure build-up in a class I operating injection well in northwest Indiana.

In recent years, numerical models have become widely used for predicting well performance. These models are specially used where conditions exist for which analytical solutions are not available or simplistic and too idealized.

Statement of the Problem

The research involves the prediction of lateral pressure increases due to the injection of Waste Pickle Liquor (WPL) into the lower Mt. Simon region. The site consists of two injection wells that are in close proximity to one another, separated by 2000 ft. The site is located in Porter County, Indiana on the south edge of Lake Michigan (Figure 10, Appendix B).

Due to the nature of the injection, an increase in pressure in the lower soil strata and lubrication caused by the injected liquid waste in earth layers, could prompt an artificial earthquake in some areas of the country especially near the fault lines. Earthquakes are not the only concern that could be associated with an injection operation. The spread of contamination in the natural groundwater and agriculture and municipal subsurface water is also a major issue for the U.S. Environmental Protection Agency (EPA). The EPA outlines the following information to be included as a part of the report submitted, for an application of permit for injection well activities:

1. Geologic Assumptions
2. Hydrologic Assumptions
3. Chemical Assumptions
4. Boundary Conditions
5. Computer Simulator or Code
6. Simulator results versus Analytical solutions.

Additional information is required accompanied with the report to grant permission for injection well activities by Petitioners. The discussion of the other information is outside the scope of this report. However the sixth requirement mentioned above has been the focus of this investigation in comparing results and the validity and adequacy of computer codes (analytic and numerical), that are being employed by industry for modeling purposes.

Scope of the Investigation

This report deals with the early stages of planning and permitting which allows the prediction of injection well effects immediately following a historical operating period assuming a 20-year future operating period.

A more detailed explanation of the scope of this research is as follows:

1. The study of site geology and formation in the vicinity of the injection wells.

2. Providing information on the physical and chemical properties of injected Waste Pickle Liquor (WPL) for both wells.
3. The list of the assumptions made for calculations and comparison.
4. The study of the literature available on pressure increases and using the empirical formulas to determine the future pressure build-up and its radius of influence (Warner, 1979) as the source for analytical solutions.
5. Introduction of computer modeling used for site analysis and its computation results as a source for numerical analysis.
6. Comparison of analytical computation of the site analysis with that obtained by computer modeling (numerical method) to draw the final conclusion and recommendation for this study.

CHAPTER II

REVIEW OF LITERATURE

Until the mid 1960's, the subject of the technical guide was described as deep well disposal. Some still use this terminology. However, the majority now seem to prefer the terminology subsurface of underground injection of wastewater or waste liquid.

When used in this context, the word "deep" cannot be given any specific value, but refers to the depth required to reach a porous, permeable, saline water bearing rock stratum that is vertically confined by relatively impermeable beds. The minimum depth of burial, necessary thickness of a confining strata, and the minimum salinity of water in the injection interval must be determined in each individual case.

Unregulated disposal of municipal and industrial wastes through shallow wells into strata containing potable ground water is predicted, in spite of its obvious undesirability (TEMPO, 1973). In contrast to this practice, the subject here is the controlled emplacement of wastewater into the subsurface in such a manner that the hazard to the drinking water sources and other resources is minimized. Although much of the technology described in the engineering guide is applicable to oilfield brine disposal, oilfield brine injection is excluded from consideration because of differences in regulation and practice that make it impractical to treat it simultaneously with other industrial and municipal wastewater injection methods.

Historical Uses

It is not certain where controlled wastewater injection was first practiced outside of the oilfield, but Harlow (1939) described in a published article the problems encountered by a chemical company in disposing of waste brine from chemical manufacturing by subsurface injection. Inventories by various individuals and groups have succeeded in locating no more than four such wells constructed prior to 1950. A 1963 inventory by Donaldson (1964) listed only 30 wells. Subsequent inventories published in 1967 (Warner, 1967), 1968 (Ives and Eddy, 1968), 1972 (Warner, 1972), and 1974 (US., EPA, 1974) listed 110, 118, 246, and 278 wells respectively. The most recent inventory (Reeder, et al, 1975) showed that a total of 322 industrial and municipal injection wells had been drilled up to January, 1975 and 209 of these were reportedly operating at that time. The geographic distribution of these wells and their operating status is shown in table 1.

Of the injection wells that have been constructed, few are shallower than 1,000 feet (table 2). That is

TABLE 1

DISTRIBUTION AND OPERATING STATUS OF INJECTION WELLS IN THE UNITED STATES (REEDER, ET AL., 1975)

AREA	TOTAL NO. WELLS	O	NOP	NOUP	DN	PND	PC	SNA
REGION II								
New York	4	1			3			
REGION III								
Pennsylvania	9	0	9					
West Virginia	7	6			1			
REGION IV								
Alabama	5	2			3			
Florida	10	4	1		3			
Kentucky	3	2	1					
Mississippi	2	1						
North Carolina	4		1		3			
Tennessee	4	2		1				
REGION V								
Illinois	8	4		1				
Indiana	13	11		1				
Michigan	34	21	4	3	5	1		
Ohio	10	6	1		3			
REGION VI								
Arkansas	1							
Louisiana	85	52	8		5	19	1	
New Mexico	1							
Oklahoma	15	10		1	4			
Texas	124	57	12	6	16	8	18	7
REGION VII								
Iowa	1							
Kansas	30	21		2	7			
REGION VIII								
Colorado	2		1					
Wyoming	1							
REGION IX								
California	5	4		1				
Hawaii	4	1			2	1		
Nevada	1							
TOTAL	383	205	38	16	55	29	19	7

KEY:
O: Operating
NOP: Not operating, plugged
NOUP: Not operating, unplugged
DN: Drilled, never used
PND: Permitted, not drilled
PC: Permit cancelled, never drilled
SNA: Status unknown

TABLE 2

WELL COMPLETION DEPTHS OF 259 WELLS (MODIFIED AFTER U.S. ENVIRONMENTAL PROTECTION AGENCY, 1974)

DEPTH	NO. WELLS	PERCENTAGE
0 - 1000	20	7.7
1001 - 2000	56	21.6
2001 - 3000	33	12.7
3001 - 4000	34	13.1
4001 - 5000	39	15.1
5001 - 6000	44	17.0
6001 - 7000	18	6.9
7001 - 8000	12	4.6
8001+	3	1.2

principally because injection intervals are selected so that they are sufficiently deep to provide adequate separation from potable surface water which usually occurs at shallow depths. On the other hand, few wells deeper than 6,000 feet have been constructed because of cost and because satisfactory intervals have usually been found at lesser depths.

Using data from the 1973 survey, Warner and Orcutt (1973) estimated that 60 percent of the wells that had been operated up to that time had injected less than 100 gallons per minute (computed as if the wells were operated continuously 24 hours per day 365 days per year) and 95 percent were injecting less than 400 gallons per minute. Warner and Orcutt (1973) also found that virtually all wells had injected at less than 1,500 psi and 78 percent had injected at less than 600 psi.

Geologic and Hydrologic Environment

Knowledge of geologic and hydrologic characteristics of the subsurface environment at an injection well site and in the surrounding region is fundamental to the evaluation of the suitability of the site for wastewater injection and to the design, construction, operation and monitoring of injection wells. In defining the geologic environment, the subsurface rock units that are present are described in terms of their lithology, thickness, areal distribution, structural configuration and engineering properties. The chemical and physical properties of subsurface fluids and the nature of the local and regional subsurface flow system comprise the hydrologic environment. In addition, natural underground resources of (present or future), of potential value are identified to avoid endangering them through wastewater injection.

Stratigraphic Geology

The study of the composition, sequence, thickness, and areal correlation of the rock in a region is known as stratigraphic geology or stratigraphy.

Rocks are described in terms of their origin and their lithology, the latter characteristic being defined by their composition and texture. By origin, the three broad rock types are classified as igneous, metamorphic, and sedimentary. While nearly all rock types can, under favorable circumstances, be capable of acting as injection intervals, sedimentary rocks, particularly those deposited in a marine environment, are most likely to have suitable geologic and engineering characteristics. These characteristics are sufficient porosity, permeability, thickness, and areal extent to permit the rock to act as a liquid storage reservoir at safe injection pressures.

Rock Types

Sandstone is a sedimentary rock commonly porous and permeable enough in the unfractured state to be suitable injection reservoirs.

Unfractured shale, clay, and siltstone have been found to provide good seals against the upward or downward flow of fluids. Limestone and dolomite may also be satisfactory fluid containing beds; but these rocks commonly contain fractures or solution channels, and their adequacy must be determined in each case (Warner and Lehr, 1977).

Nearly all types of rock mass can, under favorable circumstances, have sufficient porosity and permeability to accept large quantities of injected wastewater.

Engineering Properties of Rocks

In order to make a quantitative evaluation of the mechanical response of the subsurface environment to wastewater injection, the engineering properties of the reservoir rocks must be determined or estimated. These properties include porosity, permeability, compressibility, temperature, and state of stress. Each of these are described below.

Porosity

Porosity is defined as:

$$n = \frac{V_v}{V_t} = \frac{\gamma_d \cdot w}{\gamma} \qquad \text{(dimensionless)} \qquad (1)$$

where: n = porosity expressed as decimal fraction

V_v = volume of voids

V_t = total volume of rock sample

γ_d = dry density

w = moisture content

γ = wet density

Porosity is also expressed as a percentage. Porosity may be total porosity or effective porosity. Total porosity is a measure of all space; effective porosity is based on the volume of interconnected voids.

Porosity may also be classified as primary or secondary. Primary porosity includes original intergranular or intercrystalline pores and the porosity associated with fossils and bedding planes. Secondary porosity results from fractures, solution channels, and recrystallization and dolomitization.

Porosities in sedimentary rocks range from over 20 percent in sand to less than 5 percent in lithified sandstones. Dense limestone and dolomites may have almost no porosity.

Permeability

The permeability of a rock is a measure of its capacity to transmit a fluid under applied potential gradient. As with porosity, intergranular permeability is influenced by the properties of rocks that are composed of grains (sands, sandstones, shales, etc.). However whereas porosity is not theoretically dependent on grain size, permeability is highly dependent on this property.

Quantitatively, permeability is expressed by Darcy's Law which is as follows:

$$\bar{k} = \frac{Q\mu}{A p g} \quad \frac{dL}{dh} \tag{2}$$

where:

Q = flow rate through porous medium

A = cross-sectional area through which flow occurs

μ = fluid viscosity

p = fluid density

L = length of porous medium through which flow occurs

h = fluid head loss along L

g = acceleration of gravity

k = coefficient of permeability

A simpler form of Darcy's Law used in shallow ground water studies is as follows:

$$k = \frac{Q}{A} \cdot \frac{dL}{dH} \qquad \left[\frac{L}{T}\right] \tag{3}$$

where k = the hydraulic conductivity.

However, the permeability of rock mass when there are three mutually perpendicular sets of fractions with parrallel walls, all with identical aperture and spacing and ideally smooth, the permeability of the rock mass is theortically expressed by:

$$k = \frac{\gamma}{6\ \mu} \cdot \left(\frac{e^3}{S}\right) \tag{3A}$$

s = spacing between fractures

e = aperture (interwall seperation)

γ = fluid density

and other symbols are as previously defined.

The density and viscosity of the aquifer fluid do not appear in the above equation because they are incorporated as part of the hydraulic conductivity value. In cgs units, hydraulic conductivity is in cm/sec. The U.S. Geological Survey units for hydraulic conductivity is feet/day and formerly was gallons/day x ft^2 (meinzers) (Warner and Lehr, 1977).

Compressibility

The compressibility of an elastic medium is expressed as follows:

$$\beta = \frac{-\delta V}{V \delta p} \qquad \left(\frac{F}{L^2}\right)^{-1} \tag{4}$$

where:

β = compressibility of medium $[\text{pressure}]^{-1}$

V = volume

p = pressure

The compressibility of an aquifer includes the compressibility of the aquifer skeleton and that of the contained fluids. To account for the compressibility of both the fluid and aquifer, petroleum engineers often arbitrarily use compressibility (c), which ranges from 5 x 10^{-6} to 10 x 10^{-6} psi^{-1} as compared with the compressibility of water alone which is about 3 x 10^{-6} psi^{-1}. Van Everdinger (1968) uses this procedure in selecting a fluid and rock compressibility of 6 x 10^{-6} psi^{-1} for the example calculations that he presents.

Temperature

The temperature of the aquifer and its contained fluids is important because of the effect that temperature has on fluid properties. The temperature of shallow groundwater is generally about 2^0 to 3^0 greater than the mean annual air temperature. Figure 1 shows the approximate temperature of groundwater in the United States. Below the shallow groundwater interval, the temperature increases at a rate of about 2^0 F per 100 feet of depth, but the rate of increase is quite variable and may be from as much as 5^0 F to less than 1^0 F per 100 feet of depth (Levorsen, 1967). This rate of temperature increase with an increasing depth is known as the geothermal gradient. Estimation of temperature at a specific location and depth is fully explained by Warner and Lehr (1977).

State of Stress

Warner (1977) states that in a sedimentary rock sequence, the total normal vertical stress increases with depth of burial under increasing thickness of rock and fluid. It is commonly assumed, and the validity of the assumption can be verified, that the normal vertical stress increases at an average of about 1.2 psi/ft of depth. The horizontal stresses may be greater or less than the vertical stress, depending on geologic conditions. In areas where crustal rocks are being actively compressed, lateral stresses may exceed vertical ones. In areas where crustal rocks are not in active compression, lateral stresses should be less than the vertical stress. The basis of estimating lateral stress prior to drilling of a well is hydraulic fracturing data from nearby wells and/or knowledge of the tectonic state of the region in which the well is located.

In order to predict the pressure at which hydraulic fracturing or fault movement would be expected to occur, it is necessary to estimate the state of stress at the depth of the injection horizon. On the other hand, determination of the actual fracturing pressure allows computation of the state of stress (Rehele, 1964).

The equation form for total normal stress across an arbitrary plane in a porous medium is given by Hubbert and Willis (1972) as:

$$s = p + \delta \qquad \left(\frac{F}{L^2}\right) \tag{5}$$

where:

s = total stress

p = fluid pressure

δ = effective or intergranular normal stress

Effective stress, as defined by the above equation, is the stress available to resist hydraulic fracturing or the stress across a fault plane that acts to prevent movement on that fault. The equation shows that, if total stress remains constant, an increase in fluid pressure reduces the effective stress and a decrease in fluid pressure increases effective stress.

Properties of Subsurface Fluids

Judgement as to whether wastewater may or may not be permitted to be injected into a rock unit depends, in part on chemistry of the contained water. Chemical analysis of subsurface water are also useful for correlation of stratigraphic units, interpretation of subsurface flow systems, and calibration of borehole logs. In wastewater injection, the chemistry of the contained water is important because of the possibility of reaction with injected wastewater.

In most instances, analysis will be made for the principal ions and others on a selected basis. Table 3 lists the chemical and physical determinations that may be performed for the naturally occurring water in an injection interval.

Other physical properties that will affect the flow and pressure build up in injection wells are discussed below.

Viscosity

Viscosity is the ability of a fluid to resist flow, and is an important property in evaluating the flow rate of a fluid through a porous medium. The units of viscosity are the poise and centipoise, which is one-hundredth of a poise.

Figure 1 shows the variation in viscosity of water with temperature and salinity. Both temperature and dissolved solids content can have a significant effect. In most cases, the effects will tend to be offsetting in subsurface waters, since temperature and dissolved solids content both commonly increase with depth.

Density

The density of a fluid is its mass per unit volume. Liquid density increases with increased pressure and decreases with increased temperature. However, water changes very little within the range of pressure and temperature of interest. For instance, the density of water decreases only 0.04 gm/cm^3 between 60^0F and 210^0F (Figure 2), and increases only about 0.04 gm/cm^3 from 0 to 14,000 psi (Figure 3). A more important influence on water density in injection cases is the total dissolved solids content. Figure 4 shows the effect of various amounts of sodium chloride on density (or specific gravity).

In figures 2 and 4 presented here, specific gravity has been used in illustration instead of density. This is so, because in the metric system the numeric values of density and specific gravity are equal. Specific gravity, however, is dimensionless.

Table 3

COMMON WATER ANALYSIS PERFORMED ON SUBSURFACE WATER SAMPLES

DETERMINATION	ROUTINE ANALYSIS	INJECTION INTERVAL WATER
Alkalinity	X	X
Aluminum		X
Barium		X
Calcium	X	X
Chloride	X	X
Conductivity	X	X
Hydrogen ion (pH)	X	X
Hydrogen sulfide		X
Iron	X	X
Magnesium	X	X
Manganese		X
Potassium	X	X
Sodium	X	X
Specific gravity	X	X
Sulfate	X	X
Total Dissolved Solids	X	X

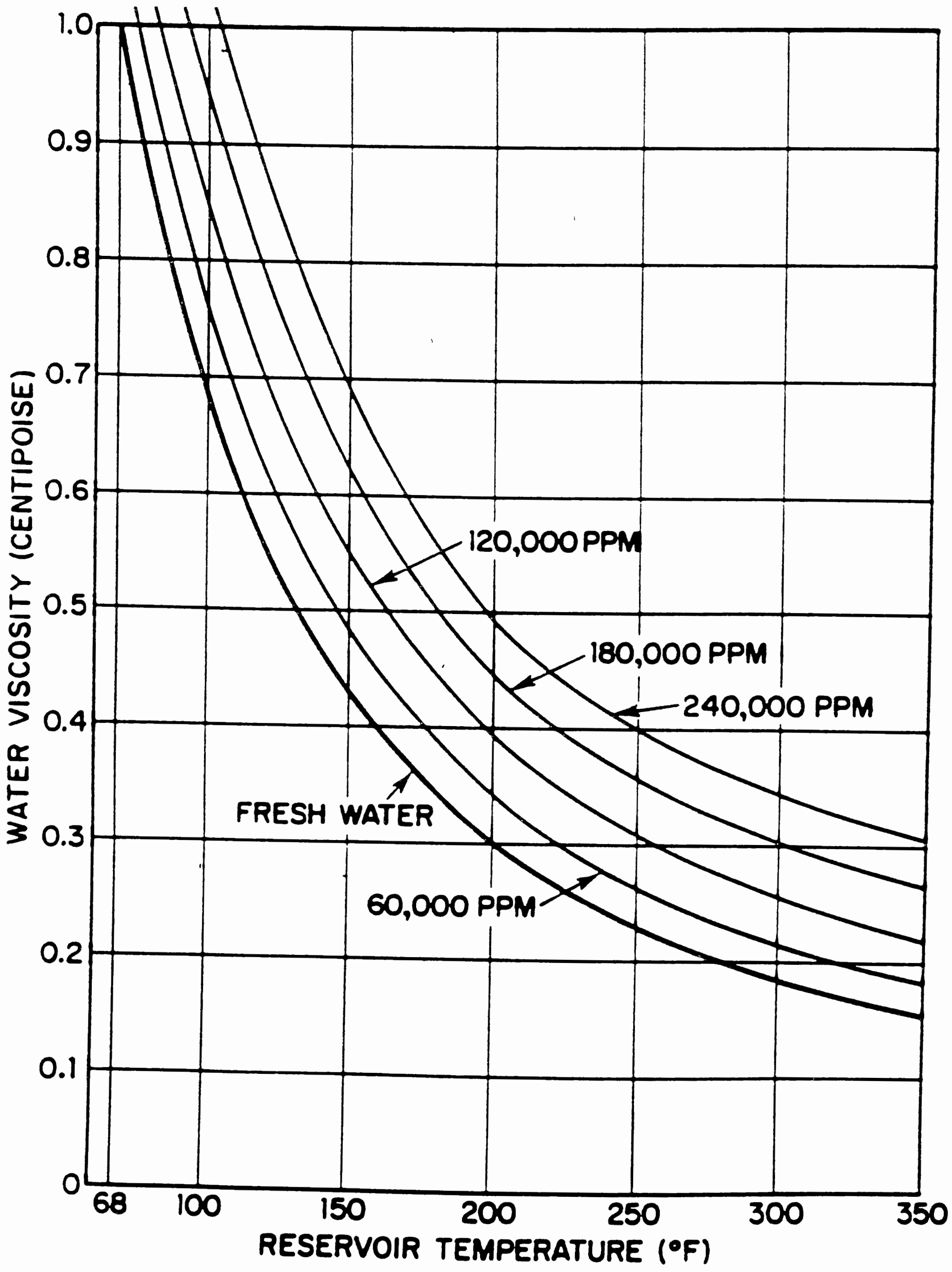

Figure 1. Water Viscosity as a Function of Temperature and Salinity

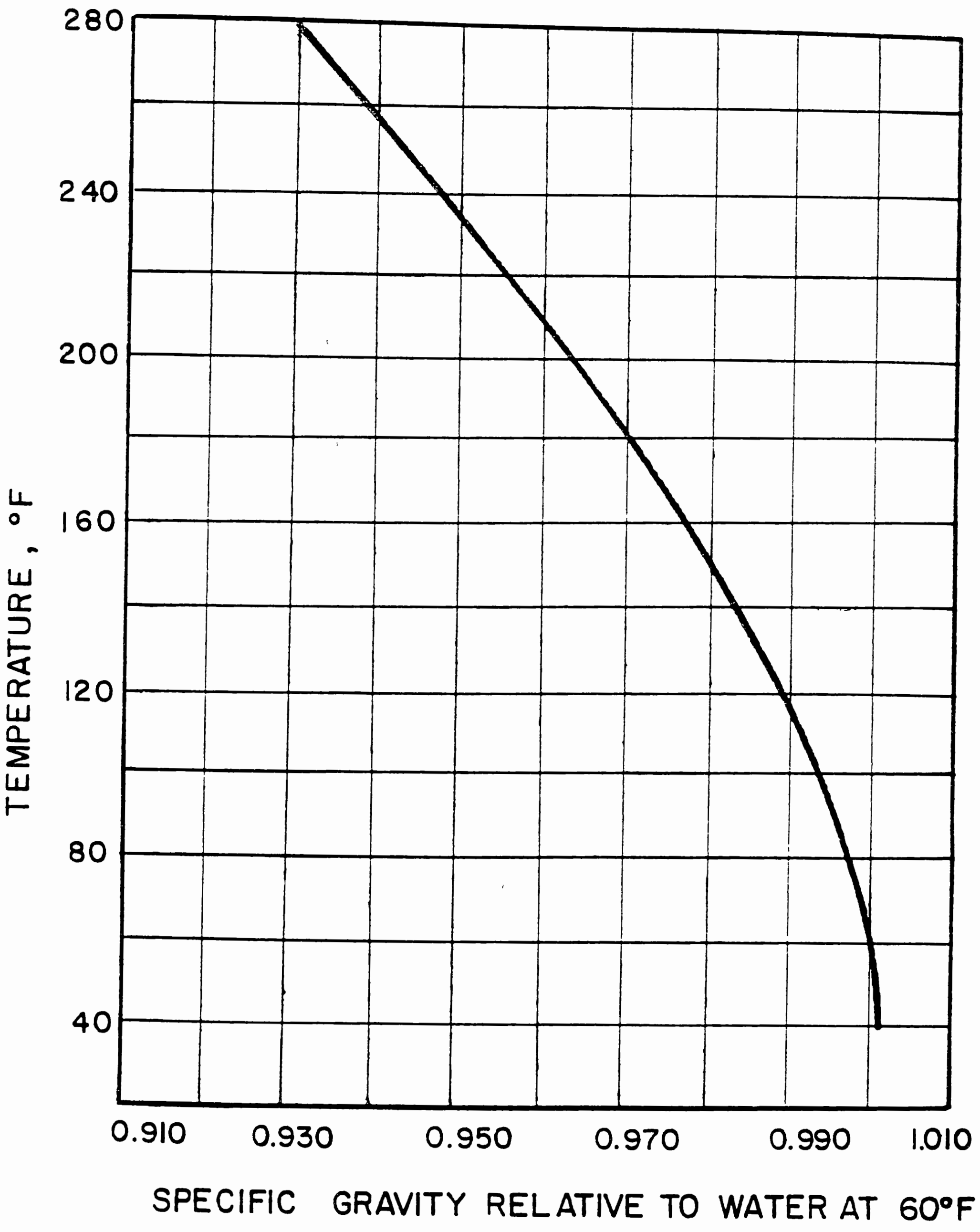

Figure 2. Specific Gravity of Distilled Water as a Function of Temperature

Pressure

The importance of fluid pressure knowledge and the method of measurement is described by Warner and Lehr, (1977) as:

Fluid can be measured directly in the borehole at the depth of the injection horizon, usually by performing a drill stem test. Fluid pressure at the injection horizon can also be measured indirectly by determining the stable water level in the borehole, then computing the pressure of the fluid column at the depth of interest.

Levorsen (1967) explains the effect of depth and specific gravity on fluid pressure. Figure 5 shows how this pressure increases with depth in a well. For example, if a well bore is filled with formation water with a dissolved solids content of 65,000 mg/liter and a specific gravity of 1.035, then fluid pressure increases at a rate of 0.45 psi/ft, and would be 450 psi at the bottom of a 1,000 ft deep water filled well. This is an average gradient, but the actual gradient can vary because of water density variations and other causes and should be determined for each specific site.

Dikinson (1953) and Berry (1973) concluded that abnormally high pressures are common in deep wells of the Gulf Coast. The high pressures in the California Coast ranges are a result of tectonic forces.

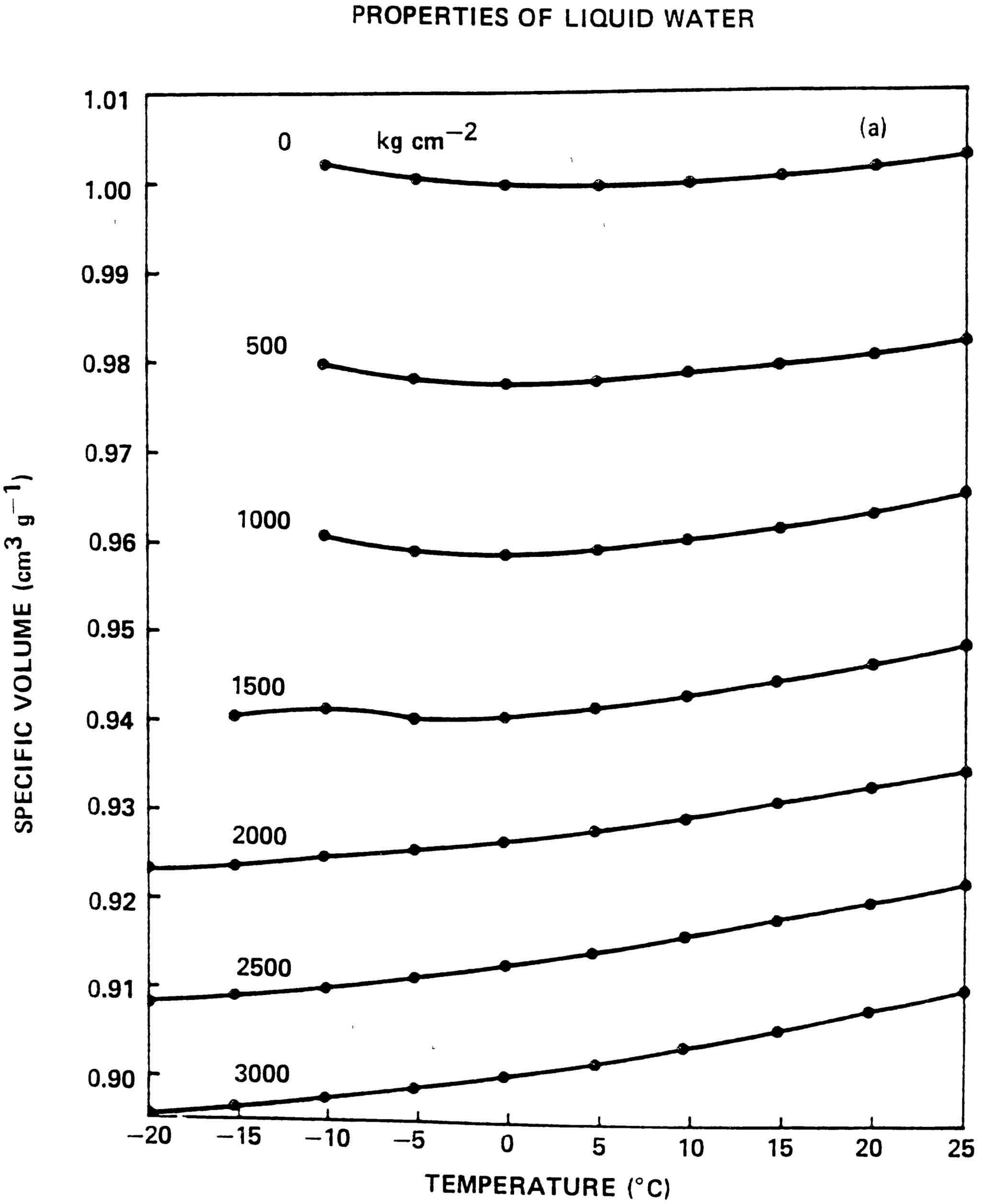

Figure 3. Specific Volume as a Function of Temperature and Pressure

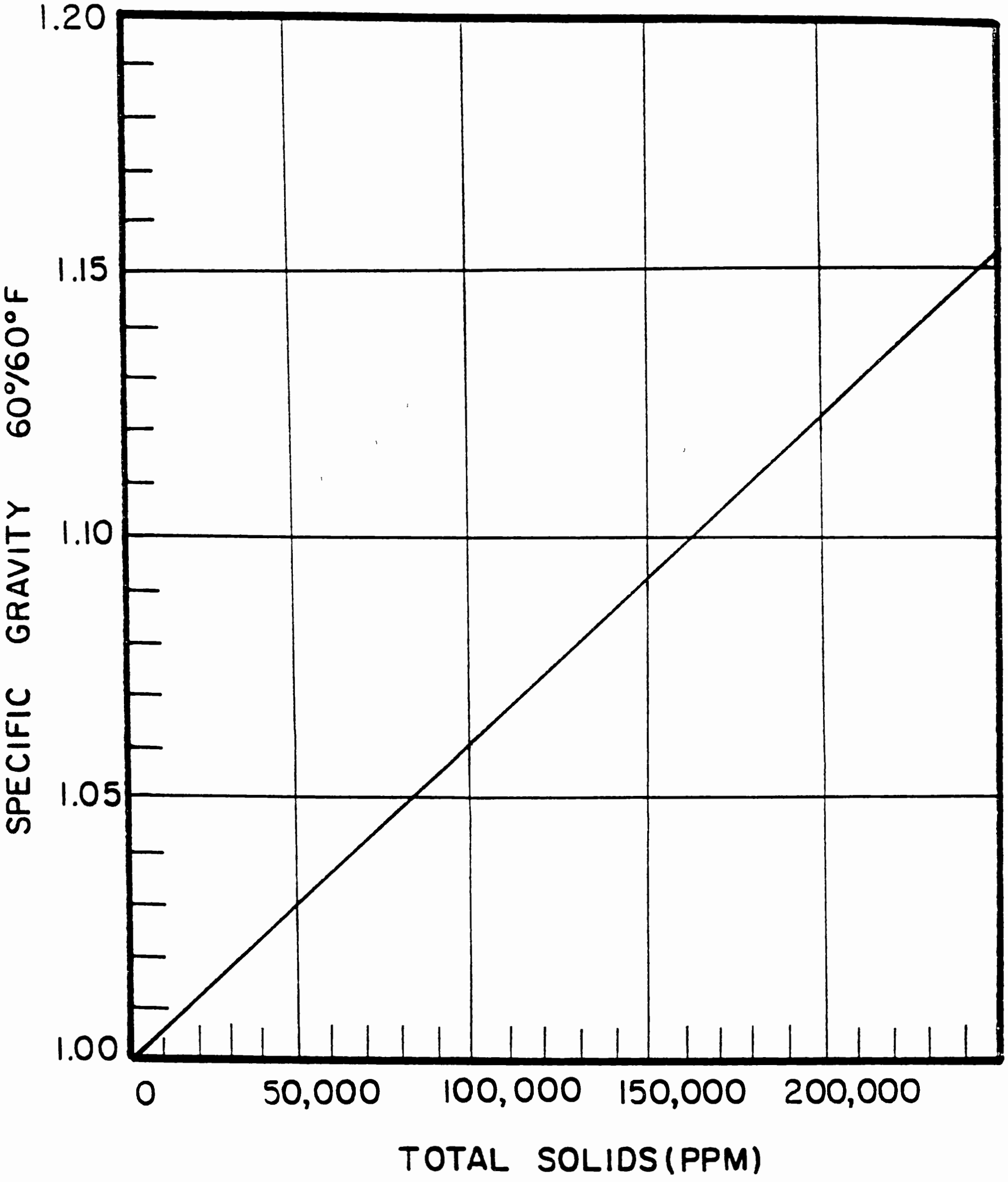

FIGURE 4. Specific Gravity of Water Versus Total Solids in PPM

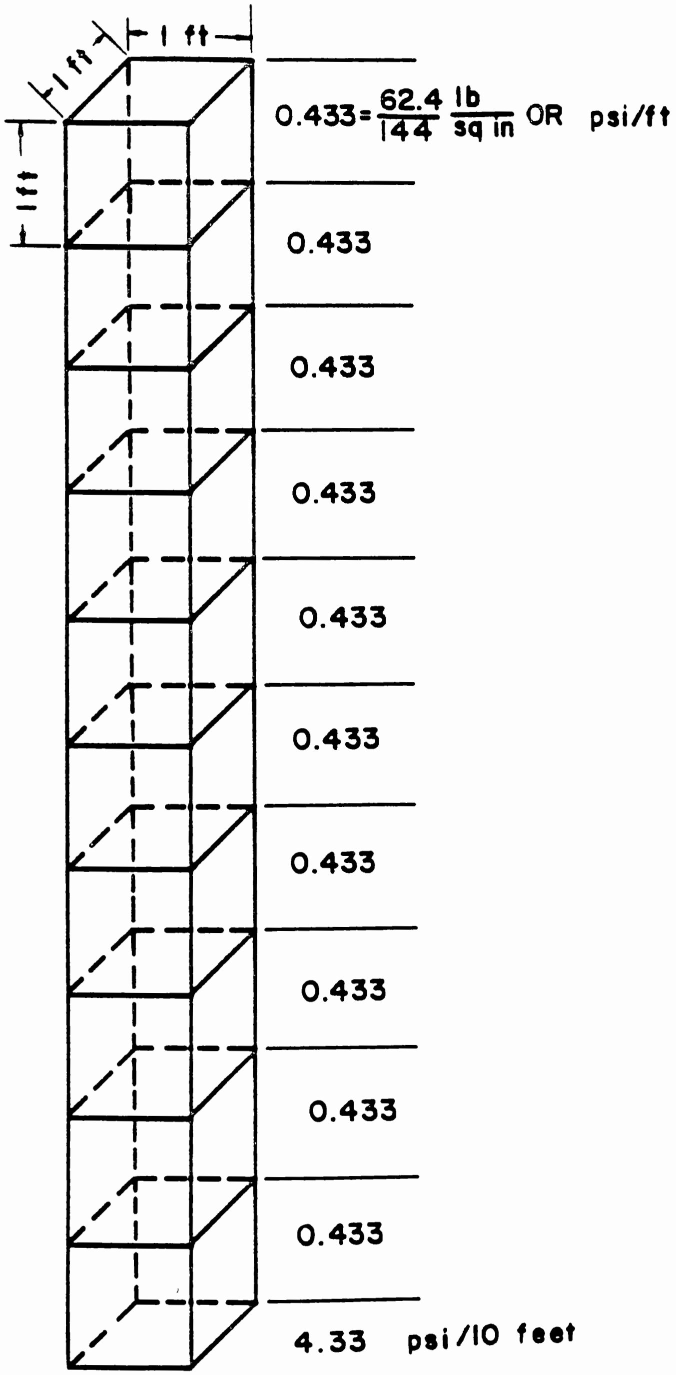

Figure 5. Hydraulic Pressure Gradient a Column of Water

Compressibility

The compressibility of the system consists of the fluid, aquifer skeleton and that of the confined fluid (water). The compressibility of water varies both with the temperature and pressure. For problems in wastewater injection, a compressibility range of 2.8 to 9 x 10^{-6} psi^{-1} are not uncommon, and 7.5 x 10^{-6} psi^{-1} is a reasonable value to assume in most cases.

Pressure Effects of Injection

Wastewater injected into a well does not move into empty voids, but it displaces existing fluids, primarily saline waste. The displacement process requires exertion of some pressure, in excess of the natural formation pressure. The pressure increase is greatest at the injection well and decreases in approximately a logarithmic manner away from the well. The amount of excess pressure required and the distance to which it extends depends on the properties of the formation and fluids, the amount of fluid being injected, and the length of time that the injection has been going on. The pressure or head changes resulting from injection are added to the original regional gradients to obtain a new potentiometric surface map that depicts the combined effects of the regional plan and local disturbances.

To compute the rate of pressure change in a well during injection intervals, Darcy's Law must be combined with the continuity equation so that time and the compressibility of the aquifer and aquifer fluids may be taken into account.

The solution first formulated and still most widely used for predicting the pressure effects of a well pumping from or injecting into an aquifer assumes the following conditions (Warner and Lehr,1977; Kruseman and DeRidder 1970):

1. The aquifer is, for practical purposes, infinite in areal extent.
2. The aquifer is homogeneous, isotropic, and of uniform thickness over the area of influence.
3. Natural flow in the aquifer is at a negligible rate.
4. The aquifer is sufficiently confined so that the flow across confining beds is negligible.
5. The well penetrates the entire thickness of the aquifer.
6. The well is small enough that storage in the well may be neglected and that removed from or placed in storage in the aquifer is discharged or taken in instantaneously with a change in the hydraulic head.

This is a formidable list of assumptions, which are obviously not completely met in any real situation. However, if one reviews the characteristics of many aquifers used for waste injection, water supply and other purposes, it can be concluded that for practical purposes they probably comply sufficiently with the assumptions.

The equation that describes the response of such an aquifer to a single injection well is then (Ferris, et al, 1962; Kruseman and DeRidder, 1970; Lohman, 1972):

$$\triangle h = \frac{Q}{4\pi T}\left(-0.577216 - \log_e u + u - \frac{u^2}{2.2!} + \frac{u^3}{3.3!} - \ldots\right) \quad (6)$$

$$\triangle h = \frac{Q}{4\pi T} E(u)$$

where: $u = \frac{r^2 S}{4Tt}$ [dimensionless]

and:

$\triangle h$ = hydraulic head change at radius r and time t

Q = injection rate

T = transmissivity

S = storage coefficient

E(u) = well function

t = time since injection began

r = radial distance from well bore to point of interest.

For large values of time, small values of radius of investigation, or both, equations above can be reduced to:

$$\triangle h = \frac{2.30\ Q}{4\pi T} \times \log \frac{2.25Tt}{r^2 S} \quad [\ L\ ] \quad (7)$$

The equations above are not unitized; therefore, any consistent units can be used. The equation equivalent to the later equation above is:

$$\triangle p = \frac{162.6 Q\mu}{\bar{k}b} \left[\log \frac{\bar{k}t}{\phi\mu c r^2} - 3.23\right] \quad [\text{ PSI }] \qquad (8)$$

$\triangle p$ = reservoir pressure change at radius r and time t [PSI]

Q = injection rate [bbl/day]

μ = viscosity [centipoise]

$\bar{k}$ = average reservoir permeability [millidarcys]

b = reservoir thickness [ft]

t = time since injection began [hours]

c = reservoir compressibility [psi^{-1}]

r = radial distance from well bore to point of interest [ft]

ϕ = average reservoir porosity [decimal]

Two very important characteristics of the equations presented above are that individual solutions can be superimposed, and the hydrologic boundaries such as faults can be simulated by a properly located imaginary well. Solutions can be easily analyzed because the effect of boundaries is analogous to that of properly located pumping or injection wells, the existence of boundaries can be detected by observing aquifer response to injection or pumping or, conversely, the effects of known or suspected boundaries can be estimated.

Dimensions and Units of Measurements

In many fields of engineering and science, units of measurements are used to express the value and sense of measurement for chemical or physical properties that are used in an equation.

Upon examination, it can be ascertained that most of the troublesome units of measurements are composed of one or more of three primary quantities, length [L], mass [m] and time [t]. These quantities or dimensions are expressed, for example in metric units, centimeters, grams, seconds (C.G.S. system), or English units, feet, pounds, seconds (F.P.S. system), or multiples and subdivisions of these. Other primary quantities (e.g. temperature [T]) also exist, but are less frequently encountered (Warner and Lehr, 1977).

In practicing in the field of wastewater injection and other applied fields as civil and chemical engineering, both systems of units, metric (M.K.S.) and SI are used. The method of conversion of the units from one system of measurement to another is beyond the scope of this report, but a conversion table has been provided in appendix D for informational purposes only. Throughout this report both systems of measurement and their conversion from one to another has been used, due to the units in which analysis data was received.

Summary

When wastewater is injected into deep wells for disposal, it can pose a serious environmental threat unless the injection process is carefully planned and executed from start to finish. Part of the process in a successful injection operation is estimation of pressure build up in the well, and traveled distance by the contamination in the groundwater system. The literature collected in this chapter is intended to provide the basic understanding of the pressure build up theory and its related equations developed by several scientists in this field. There are other considerations and studies involved in the operation of a site injection operation that have not been discussed here, such as evaluation which includes drilling data and its methods, pre-injection testing, operating programs, start up operation, monitoring and many others. This is not due to their importance being ignored, but their discussion is beyond the scope of this report.

The equations listed in this chapter are basic and fundamental, their introduction was felt essential, since the specific equations for various situations listed in the next chapter are derivations of these basic equations.

CHAPTER III

ANALYTICAL MODELS

THEORY OF PRESSURE BUILDUP

The basic equation governing steady state fluid flow through an aquifer is the Darcy equation. Combination of the Darcy equation with the continuity equation and an equation of state allows development of solutions for cases in which pressure increases with time (unsteady or transient conditions).

The basic differential equation for the unsteady radial flow of a slightly compressible fluid from an injected well (or to a pumping well) is (Matthews and Russell, 1967):

$$\frac{\delta^2 P}{\delta r^2} + \frac{1}{r} \frac{\delta P}{\delta r} = \frac{\phi \mu c}{k} \frac{\delta P}{\delta t} \qquad (9)$$

In the development of the equation above, the following assumptions were made:

1. Horizontal flows
2. Negligible gravity effects
3. A homogeneous and isotropic reservoir
4. A single fluid of small and constant compressibility

The equations presented in this report are solutions of this equation or a similar equation, for various selected conditions.

Throughout this thesis, pressure buildup equations are written using dimensionless pressure (P_D) and dimensionless time (t_D). These dimensionless quantities are groups of variables that commonly occur in buildup equations and which can be replaced by a single term dimensionless time, for the units and parameters listed in table 4.

$$t_D = \frac{6.33 \times 10^{-3} kt}{\phi \mu c r^2} \qquad (10)$$

In unsteady stable or transient flow equations, dimensionless pressure (P_D) is a function of dimensionless time and other quantities depending on the particular buildup solution. It is defined for each equation in which it is used.

Infinite Confined Reservoirs

For many practical situations, an adequate approximation of the pressure buildup resulting from well injection can be obtained by assuming that:

1. The receiving reservoir is infinite in area extent and is completely confined above and below by impermeable beds.
2. Prior to injection the piezometric surface in the vicinity of the well is horizontal, or nearly so.
3. The volume of fluid in the well is small enough so that the effect of the well bore can be neglected.
4. The injected fluid is taken into storage instantaneously. That is, pressure effects are

TABLE 4

PARAMETER AND VARIABLES

Parameter or Variable	Symbol	Practical Units
compressibility	c	psi^{-1}
porosity	ϕ	decimal fraction
reservoir thickness	h	ft
permeability	k	md
viscosity	μ	cp
pressure	p	psi
flow rate	q	STB/D*
radial distance	r	ft
time	t	D

* STB/D = 42 gal./D

transmitted instantaneously through the aquifer.

These assumptions coupled with assumptions listed in the last section are basic to all equations in this chapter.

Constant Injection Rate (Single Well)

The equation for pressure buildup resulting from a constant rate of injection through a single well that fully penetrates the receiving aquifer (Figure 6) is (Matthews and Russell, 1967):

$$P_r = P_i + 70.6 \frac{q\mu\beta}{kh} \left[E_i \left[\frac{39.5 \ \phi c r^2}{kt} \right] \right] \qquad (11)$$

For cases where the quantity in parentheses ($1/t_D$) is less than 0.01, an adequate approximation of this equation is (Matthews and Russell, 1967):

$$P_r = P_i + 162.6 \frac{q\mu\beta}{kh} \log \left[\frac{kt}{70.4 \ \phi\beta\mu c r^2} \right] \qquad (12)$$

where:

P_r = reservoir pressure at radius r, psi

P_i = initial reservoir pressure, psi

q = flow rate, STB/D for liquid

β = formation volume factor, RB/STB for liquid

c = compressibility , psi

k = permeability, md

h = reservoir thickness

ϕ = porosity, decimal fraction

μ = fluid viscosity, CP

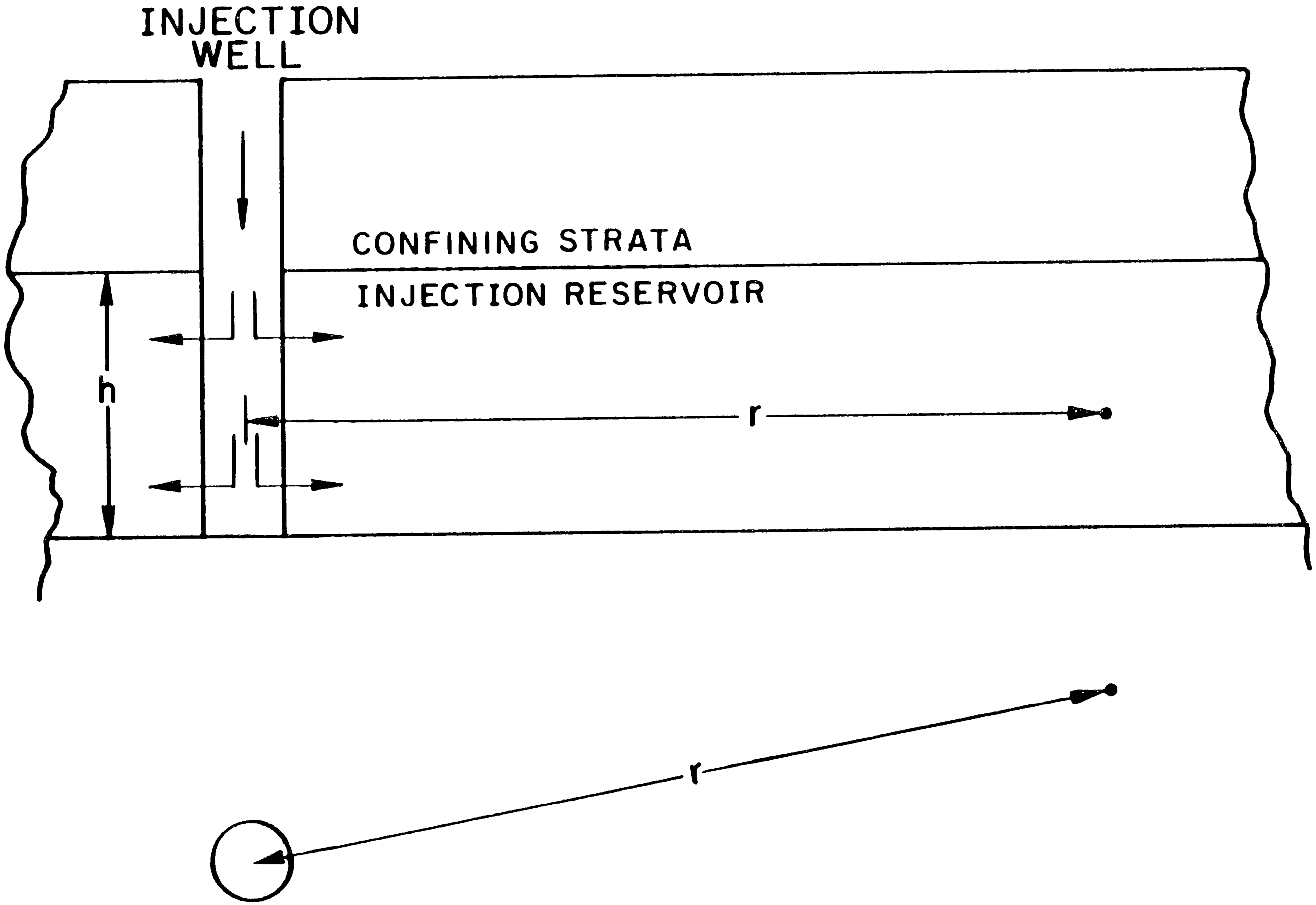

Figure 6. Profile and Plan View of a Completely Penetrating Well

r = radial distance from the well to the point of investigation, ft.

t = time, days

Variable Injection Rate (Multiple Wells)

In computing the pressure buildup caused by multiple injection wells operating at variable rates, the principle of superposition is applied twice, once for the computation of the pressure effects of each well and a second time in summing the effects of the individual wells (Warner and others,1979). The applicable equation to be used for this well arrangement is as follows:

$$P_r = P_i + \left\{ \Sigma^m_{b=1}\, \Sigma^n_{a=1}\, \frac{70.6(q_{ba} - q_{b(a-1)})\beta}{k_b h_b}\, E_1 \left[\frac{39.5\ \phi_b \mu_b c_b r_b^2}{k_b(t_b - t_{b(a-1)})} \right] \right\} \tag{13}$$

Where b is the well number, a is the time interval under consideration for well b, and q_{ba} is the rate for well b during time interval a. For cases where $1/t_D < 0.01$, an adequate approximation is:

$$P_r = P_i + \left\{ \Sigma^m_{b=1}\, \Sigma^n_{a=1}\, \frac{162.6(q_{ba} - q_{b(a-1)})\beta}{k_b h_b}\, \log \left[\frac{k_b\ (t_b - t_{b(a-1)})}{70.4\ \phi_b \mu_b c_b r_b^2} \right] \right\} \tag{14}$$

Other parameters appearing in the equations are the same as the parameters previously defined in the case of a single well and constant flow rate.

The E_1 term that is appearing in both cases of pressure buildup equation is defined as an Exponential Integral and is computed by the equation listed below:

$$E(u) = \int_u^{\infty} \frac{e^{-a}}{u}\, du = -.05772 - \ln u - \Sigma_{n=1}^{\infty} \frac{(-u)^n}{n(n!)} \qquad (15)$$

where $u = \dfrac{r^2 S}{4Tt}$

r = radial distance

S = storage coefficient

T = transmissivity

t = time in days

For the values of E for the calculations in this report see appendix D.

The equations presented here, all contain the variable ß, the formation volume factor, which is the ratio of the volume of the fluid being injected at reservoir pressure compared with the volume of standard conditions (520°R, 14.7 psi). For liquids, ß can be quite variable when the injected fluid is gas. When a highly compressible fluid is being injected, ß should be evaluated at an average reservoir pressure. The value of ß has been assumed to be 1.0 in all calculations in this report.

Factors Effecting the Well Performance

There are several conditions in the underground reservoir or the well itself that may influence calculation of pressure build up. Some of these conditions are discussed in this chapter briefly.

Wells With Skin Effects

Injection wells may suffer permeability loss in the vicinity of the well bore during construction or operation or they may experience a permeability gain. Permeability loss can result from drilling mud invasion, clay mineral reactions, chemical reactions between injected and aquifer, water, bacterial growth, etc. Permeability gain can result from chemical treatment such as acidization or from hydraulic fracturing and their mechanical simulation methods.

Partially Penetrating Wells

Partial penetration results in greater pressure build up at and near the well bore than would be experienced in a fully penetrating well for the same injection (pumping) rate. The magnitude of difference depends on the degree of penetration, the ratio of the radius of influence to aquifer thickness (r/h), the length of the completed interval, and the vertical point of investigation.

Fractured Reservoirs

It is common practice to artificially fracture injection wells, by hydraulic means, to increase their capacity to accept injected fluid. Such a fracturing will effect pressure build up, particularly near the well.

CHAPTER IV

COMPUTER MODELING

This section contains information regarding the conceptual model used to represent the actual physical and chemical system. The verification/calibration of the computer model to historic operational periods, the prediction/simulation of maximum injection pressure and flow rate to the year 2007, and the 10,000 year forecast to lateral pressure build up. The computer modeling of injection well demonstrates, using a flow and transport computer model, a prediction in future pressure build up and migration of injected fluid within the injection zone to a point of discharge over a time span of 10,000 years.

Computer Model

The computer model used to simulate the class I injection wells at this site is termed SWIFT II. It derives its name from the acronym of Sandia Waste Isolation Flow and Transport model. SWIFT II varies from SWIFT by the inclusion of the capability to handle three additional systems: two are confined dual-porosity systems, one of which is a fractured porous material, and the other is an aquifer with conductive confining beds. The third system is an unconfined aquifer with a free water surface.

Model Characteristics

SWIFT II is a fully transient three dimensional model which simulates the flow and transport fluid, heat, brine, and radionuclide chains in porous media. The primary equations for fluid, heat, and brine are coupled by fluid density, fluid viscosity and porosity. Steady state options are available for both the fluid and brine equations. Both the cartesian and cylindrical coordinate system may be used; however, the later system is restricted to two dimensions, r-z simulations. Both dual porosity and discrete - fraction models may be considered for fractured zones. Migration within the rock matrix is characterized as one - dimensional.

Mathematical Framework

SWIFT II comprises the four transport processes: fluid, heat, brine, and radionuclide chains. For a porous media, only the global (three - dimensional) process simulator is used. The local (one - dimensional) process simulator is used for the rock matrix.

The general three dimensional partial differential equation for unsteady flow of liquid in a well is described as:

$$K_x \frac{\delta^2 P}{\delta x^2} + K_y \frac{\delta^2 P}{\delta y^2} + K_z \frac{\delta^2 P}{\delta z^2} = S_s \frac{\delta P}{\delta t} \qquad (16)$$

If the flow is steady, $\frac{\delta h}{\delta t} = 0$ therefore,

$$K_x \frac{\delta^2 P}{\delta x^2} + K_y \frac{\delta^2 P}{\delta y^2} + K_z \frac{\delta^2 P}{\delta z^2} = 0 \qquad (17)$$

In radial coordinates, equation (17) becomes:

$$\frac{\delta P}{\delta r^2} + \frac{1}{r} \frac{\delta P}{\delta r} = \frac{S}{T} \frac{\delta P}{\delta t} \qquad (18)$$

The solution of second order differential equations 16, 17, and 18 will be of (Taylor's) Series expansion form from which discertization is performed by the finite - difference method using centered or backward weighing in the time and space domains. Matrix solution is performed either by Gaussian elimination or by two - line successive overrelations (TLSOR).

Finally in addition, the SWIFT II is capable of one and two dimensions models included in the three dimensional model. For single well problems, cylindrical geometry (r,z) is available. For fractural media, either dual porosity (highly fractured) or discrete fracture (faulting) geometries may be represented. The discrete fractures may be single or double sided and orientated parallel to any primary axis.

Although the numerical model is designed for three dimensions, for many applications simpler geometry is sufficient.

Computer Modeling Prediction

The above discussion demonstrated, using a flow and transport computer model, that the site conditions are such that injected fluid will not migrate vertically upward out of the injection zone or migrate within the injection zone to a point of discharge over a time span of 10,000 years. Maximum lateral and vertical movement is estimated conservatively to be 5,080 feet (0.96 miles) and 94 feet, respectively, which its comparison with analytical solution results was not the intention of this report. The 10,000 years post operational pressure build up is negligible and is not considered in this report, but the twenty year future pressure build up and its analytical counterparts are listed in appendix C.

SWIFT II Application

The application of SWIFT II was limited to the replication of a historical period of surface injection pressure given injection volumes (verification), replication of a recent operational period (calibration), and the forecasting of the pressure distribution in the Mt. Simon injection interval and the adjacent overburden for a period of 10,000 years henceforth.

Calculations estimated the waste plume radius and location during the 10,000 years. These calculations consider fluid injection, regional groundwater gradients, successfully modeling of the groundwater injection of hazardous miscible wastes at the site. The approach to modeling is conservative and predominately based upon measured geological and operational parameters.

CHAPTER V

DICUSSION OF RESULTS

The section below introduces the method of determining an area of investgation, i.e. the cone of influence. The cone of influence is defined as the radial distance from the injection well at which the pressure build up in the injection interval is greater than the pressure required to cause upward fluid movement in an abandoned well bore. The injection interval pressure distribution was analyzed using:

1. Analytical solution (pressure build up equations)
2. Numerical solution (SWIFT II Computer Software)

The results of these analysis are illustrated as figures 7 and 8.

Cone of Influence Discussion

The review radius associated with the cone of influence at the site was determined for the calculated pressure build up associated with two different time periods. They are listed below:

1. Start of injection to 1987; current pressure condition. Actual flowrate and volume used.
2. From 1987 to 2007, annual continuous flowrate are used to simulate the worst case conditions.

Assumptions for Computations

The basic assumption of steady state fluid flow for Darcy's equation were used (chapter III) in the computation of pressure build up. Other assumptions such as well condition and underground aquifer conditions were made for both analytical and numerical calculations as follows:

1. Uniform permeability throughout the aquifer and the wells
2. No skin damage during the construction of the wells or a minimal amount, such that their effects would be negligible
3. Fully penetrating wells
4. No artificial fracturing performed for capacity improvements
5. No directional leakage effects.

Calculation of Cone of Influence

The cone of influence was calculated for distances of 0 (at the well), 2, 5, 8, 10, 15, and 18 miles. The results of pressure build up using the equations in chapter III are listed in table 10 through 17 in appendix C.

The calculation of pressure build-up was performed for distances mentioned above by first calculating the value of t_D for each distance by using equation 10 in chapter III. When the value of t_D exceeded 100, a simpler form of the pressure build up equation (No. 14) was used. For the values of t_D less than 100, equation 13 has been used in the calculation of pressures at those locations. The values obtained by the use of equations 13 and 14 are accumulative values of pressure build up during the first 20 years of operation of both WPL1 and WPL2 under a variable annual flow rate. After an initial pressure has been determined for each well, the values were added to obtain the combined effect of both wells. Then the equations (11 or 12) were applied to predict the future (20 year) pressure build up under constant annual flow rates. Note should be given to equations 11 and 12 in which the pressure build up is computed for a single well under constant annual flow rates. This assumption was made since the proximity of the wells are close enough to make the two wells act as a single well in operation.

A comparison graph of computed values by the computer and, the analytical formulas for the same radial distances are provided in figure 9.

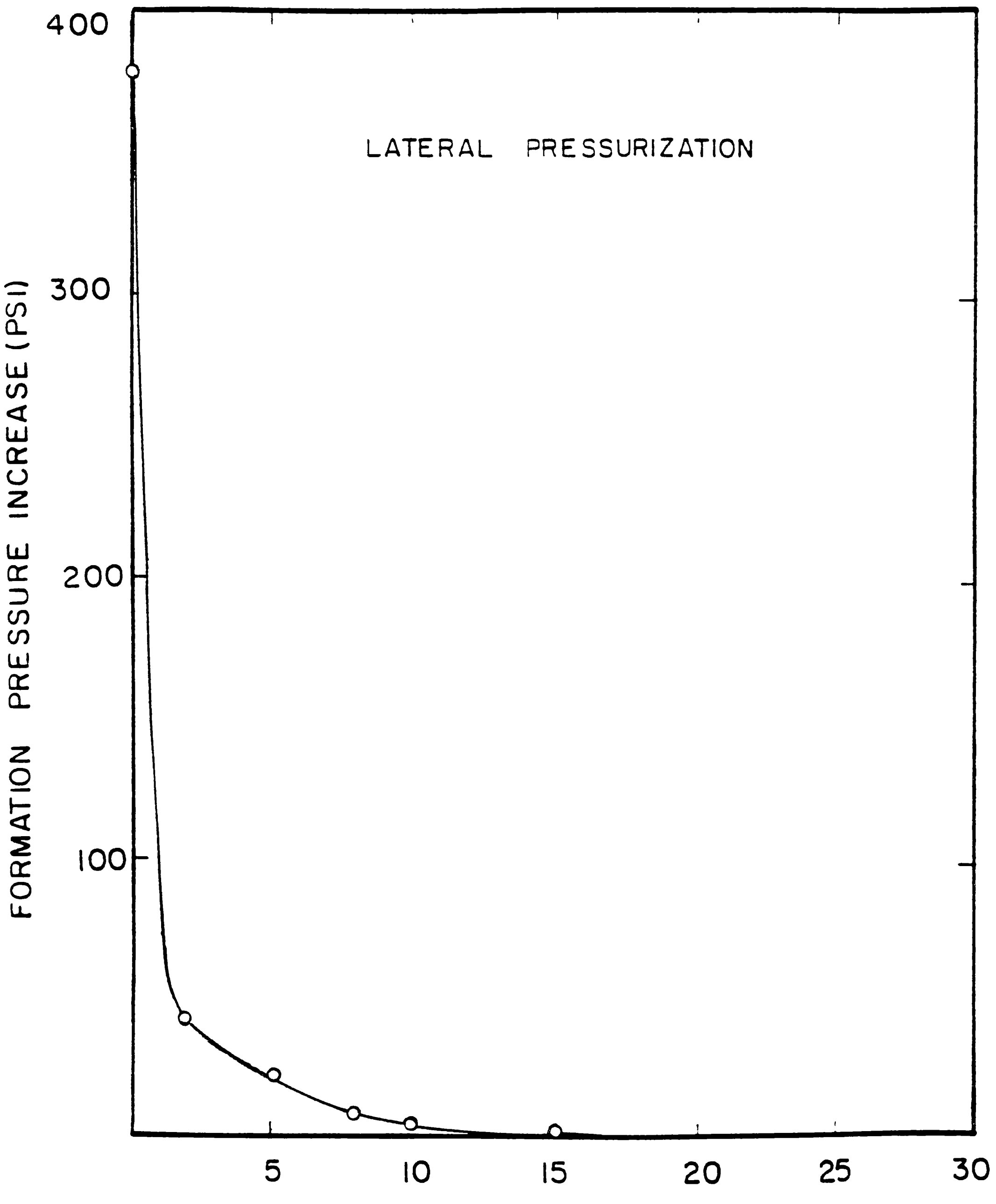

Figure 7. Lateral Pressure Distribution - Analytical Solution

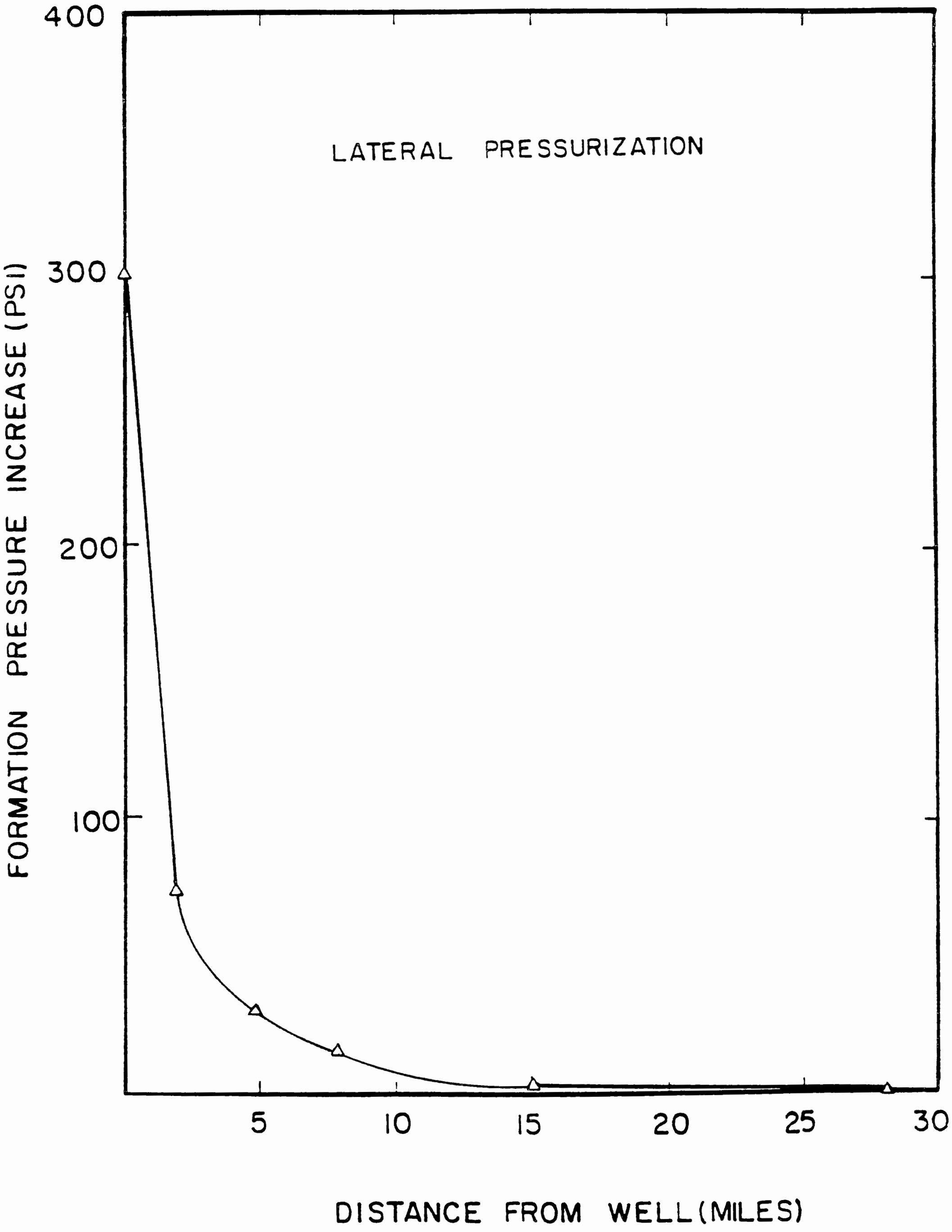

Figure 8. Lateral Pressure Distribution - SWIFT II

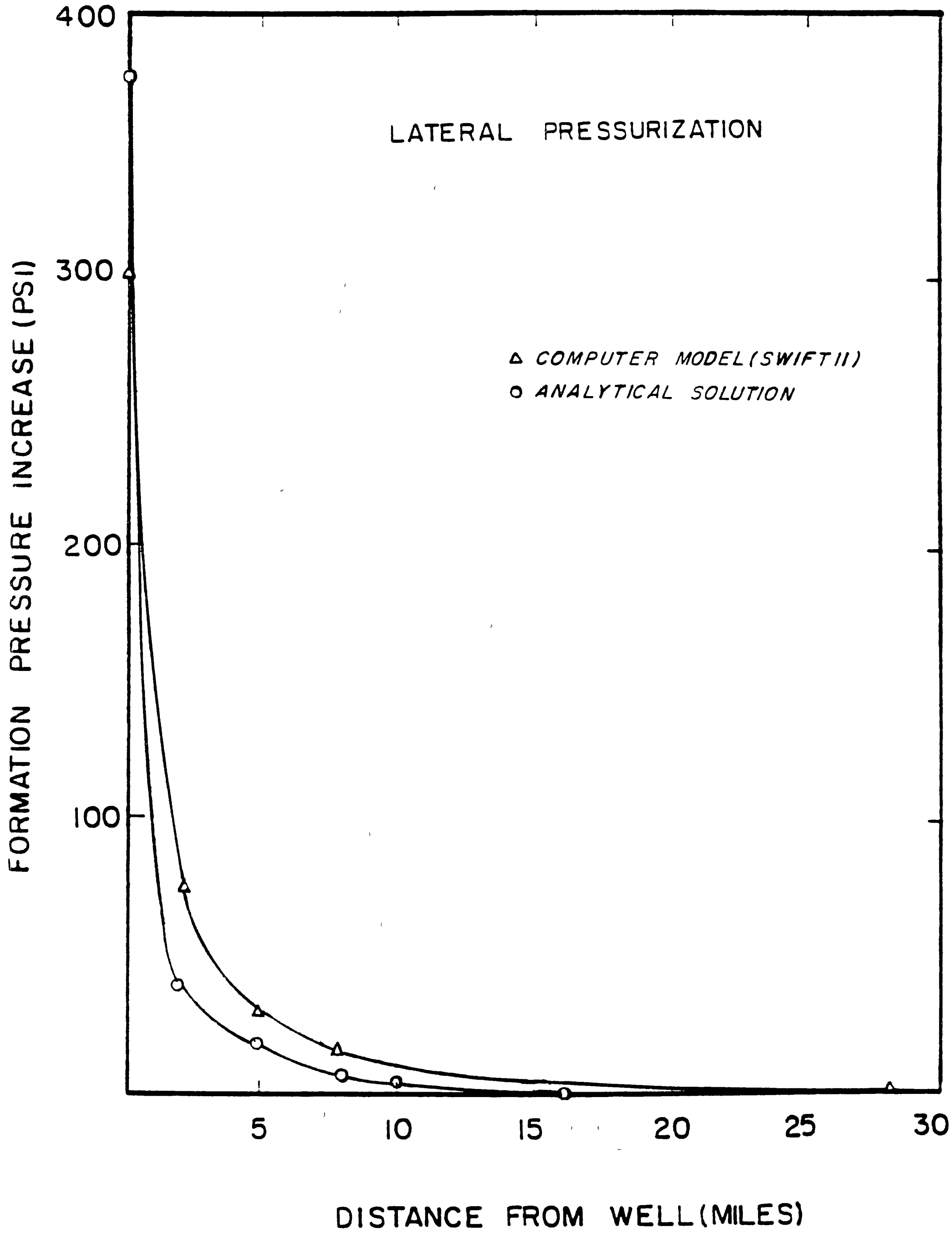

Figure 9. Lateral Pressure Distribution - Comparison Graphs

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

An evaluation of the results obtained from the two methods of calculation of pressure build up in injection wells, namely analytical solution and numerical solution, produced the following conclusions:

1. Pressure calculated at well bore by the analytical solution is higher in this case study than that obtained by the computer model solution (SWIFT II), which is on the conservative side.
2. Pressure calculated at the radial distances away from the well bore using analytic solution show drastically lower pressure values than that generated by the computer model.
3. In the present case study, zero presure zone is over predicted by the numerical model compared to the analytical solution.
4. Computer modeling simulations in most cases will produce a more realistic result compared to analytic solutions, but analytic solutions are easy to use and require less spacial and temporal hydrologic and chemical data.

For the analysis of performance and pressure build up in the calculations of injection wells the following conclusions are recommended:

1. The results obtained by the computer model for any radial distance in question should be checked by analytical formulas, in order to detect any error that may occur in the process of simulating field conditions.
2. More field tests should be performed to verify the validity of the results obtained by either method.

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APPENDIX A

SITE HYDROLOGY / GEOLOGY

Site Hydrogeology

The site is located in the northwest portion of Indiana on the shoreline of Lake Michigan. It is in an area of low relief within the bed of ancient glacial Lake Chicago. Locally, the elevation varies from 10 feet to 50 feet above the water level of Lake Michigan.

This area is part of the Northern Moraine and Lake Region which is characterized by a variety of glacial land forms. These shorelines illustrate the successively lower levels of the ancient glacial lake. In some areas there is as much as a 40 foot difference in elevation between the present shoreline of Lake Michigan and relic shorelines. The relic shorelines are capped by sand dunes which trend in an east -west arc.

Regional Hydrology

A large portion of information utilized in describing the following regional hydrology in Lake and Porter Counties was obtained from the State of Indiana Geological Survey Special Report No. 11, "Environmental Geology of Lake and Porter Counties, Indiana - An Aid to Planning", 1975.

Approximately 87 % of the total domestic water in Lake and Porter Counties is supplied by Lake Michigan. The remaining 13 % is derived from groundwater. Nearly all the groundwater is produced in the southern portion of these two counties from Quaternary and Siluro-Devonian aquifers.

The shallow Quaternary aquifer in the northern portion of the study area is not extensively utilized in the production of groundwater. Cambrian and Ordovician aquifers underlie the shallower aquifers but are not significantly developed in either county.

The discussion of Quaternary and other aquifers such as, Calumet, Valparaiso, Kankakea, Silurian and Devonian aquifers is beyond the scope of this report and their effect is not being considered in the calculations for the pressure build up, since the site proximity does not interface with these aquifers.

Geology

The regional geology of Lake and Porter County include their structural location on the northern flank of the Kankakee Arch a formational high which separates the Michigan Basin to northeast and the Illinois Basin to the southwest. The subsurface strata within this area includes approximately 4000 feet of consolidated sediments including sandstone, limestone, dolomite, and shale of Cambrian through Mississippian Age is exhibited in the regional northwest- southwest cross section. These sediments lie unconformably upon precambrian granite. The structural dip is generally southeastward at approximately 5 feet to 7 feet per mile.

Local Geology/Stratigraphy

A portion of site's Harbor Works is built on artificial fill and projects into Lake Michigan. In the vicinity, the surficial geology consists of artificial fill and unconsolidated beach deposits such as sand and gravel. Small areas of lake and swamp deposits consisting of muck, peat and marl are also present, indicating poorly drained depressional areas. Till, silty clay, and intermixed sand and gravel deposited by the Wisconsin Glacial advance comprise the majority of surficial deposits to the south of the injection site. The Kankakee Arch Sedimentary Sequence Outcrops to the northwest and southwest of the study area.

Local Geology (Injection Zone)

The basal sedimentary rock unit in Indiana is the thick and extensive Mt. Simon Sandstone. It does not crop out and occurs only in the subsurface. It extends throughout Indiana and comprises approximately 1/5 of all sedimentary rocks by volume in the state. Its thickness varies considerably from eastern to western Indiana. The Mt. Simon Sandstone gross thickness ranges from approximately 300 feet in the east to approximately 2000 feet in the west. It is 1988 +/- thick at the site.

In general throughout the study area, the Mt. Simon Sandstone is poorly sorted and consists of fine to coarse, angular to subrounded, quartz sand grains interspersed with locally concentrated shale laminae.

APPENDIX B

SITE SPECIFICS

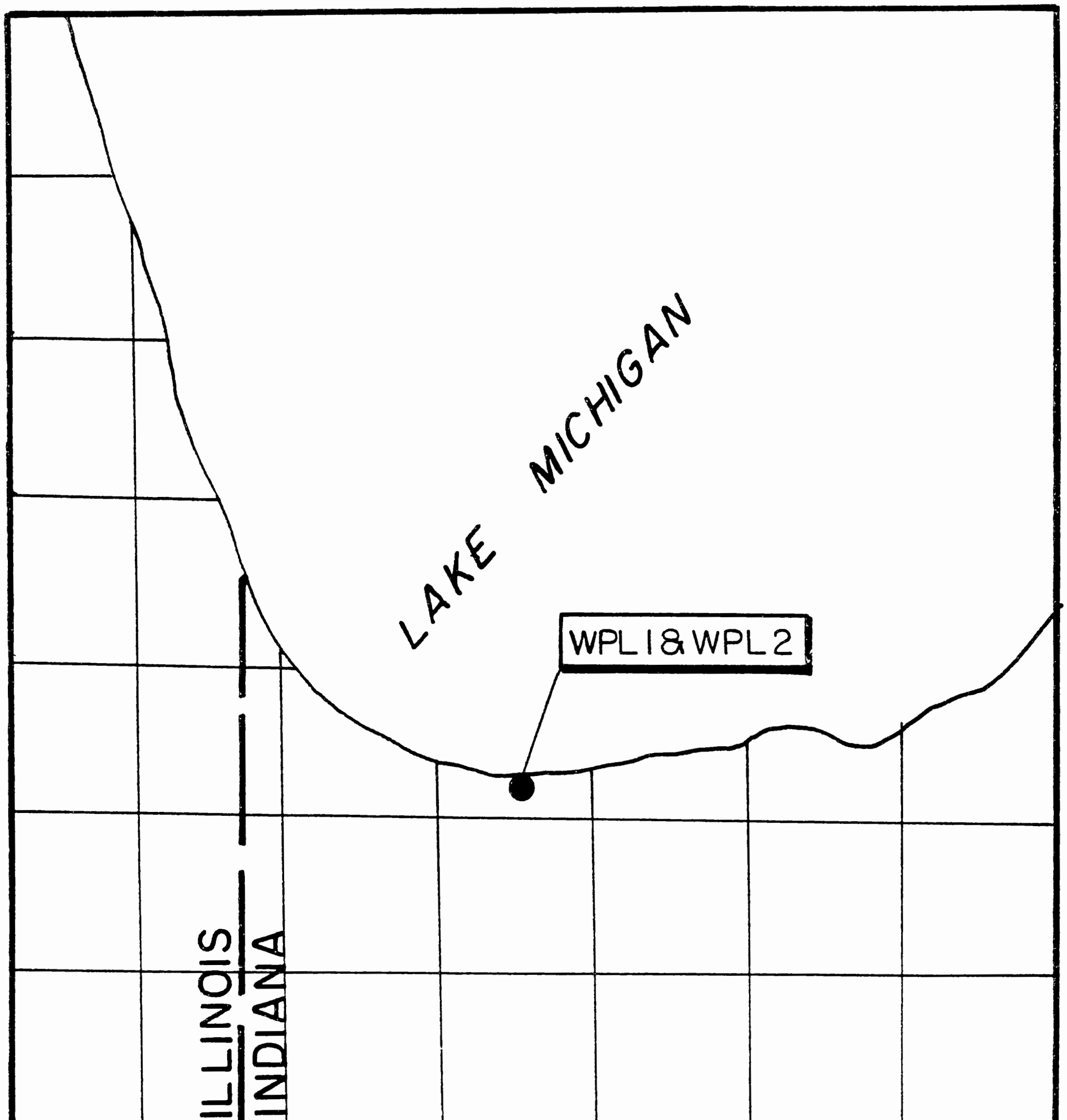

Figure 10. Location of Site

○ CEMENT, VOLUMES, FLUIDS and HOLE SIZE

□ TUBULARS and COMPONENTS

Ⓐ Cement to Surface

Ⓑ Cement to Surface

Ⓒ Annulus Inhibited Freshwater Filed

Ⓓ. Epoxy Resin Cement

Ⓔ Completion 4 3/4" Open Hole, 2631' to 4300' TD

[1] Conductor Casing: 16" Set @ 169'

[2] Surface Casing: 10 3/4" Carbon Steel Set @ 800'

[3] Protection Casing: 7" Carbon Steel 288'-2283'

[4] Injection Tubing: 3 1/2" FRP 0'-2057'
2 7/8" FRP 2058'-2631'

[5] Linner: 4 1/2", Carbon Steel & Hastelloy 2175' to 2631'

[6] Packer: Otis Interlock @ 2596'

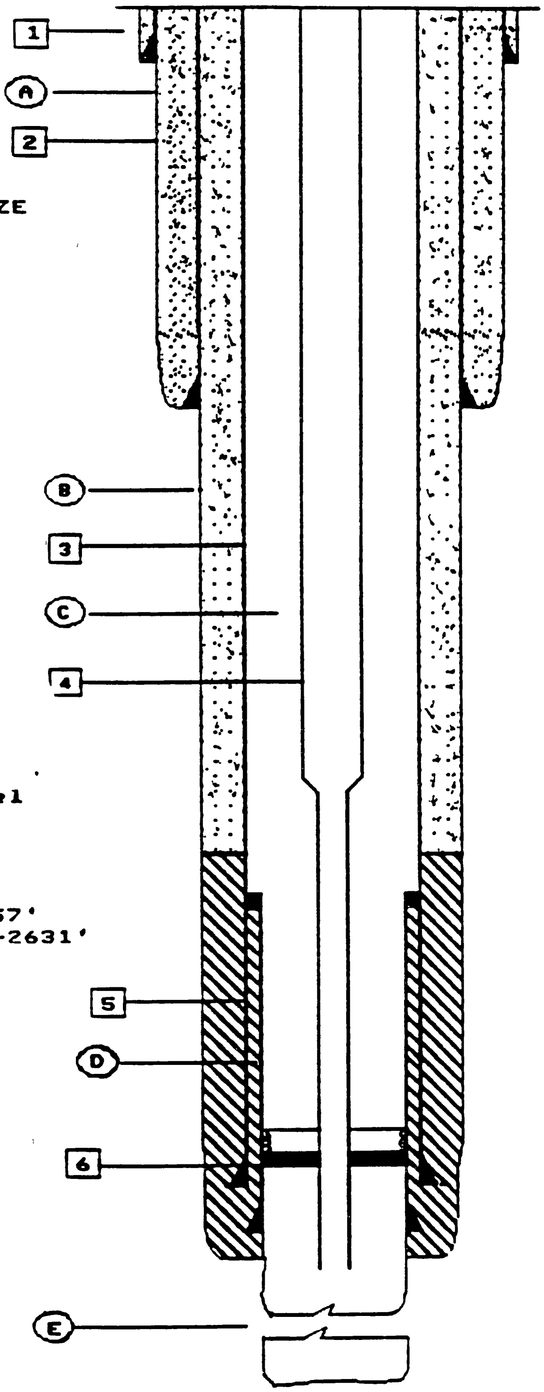

Figure 11. Well Schematic Well No. 1

○ CEMENT, VOLUMES, FLUIDS and HOLE SIZE

□ TUBULARS and COMPONENTS

Ⓐ 17 1/2" Hole, 710 Sacks Class A Cement to Surface

Ⓑ 12 1/4" Hole, 680 Sacks 50/50 Pozmix Cement to

Ⓒ Annulus Inhibited Freshwater Filed

Ⓓ. Epoxy Resin Cement 2050' to 2590'

Ⓔ Completion: 7 5/8" Open Hole, 2590' to 4385' TD

1 Conductor Casing: 20" Carbon Steel Driven to 129.5'

2 Surface Casing: 13 3/8" Carbon Steel Set @ 810'

3 Protection Casing: 9 5/8" Carbon Steel 0'- 2495'

4 Injection Tubing: 4 1/2" FRP 0'-2582'

5 Linner: 6 5/8" Hastelloy 2371'-2557'

6 Packer: Louisiana Oil Tool Set @ 2520'

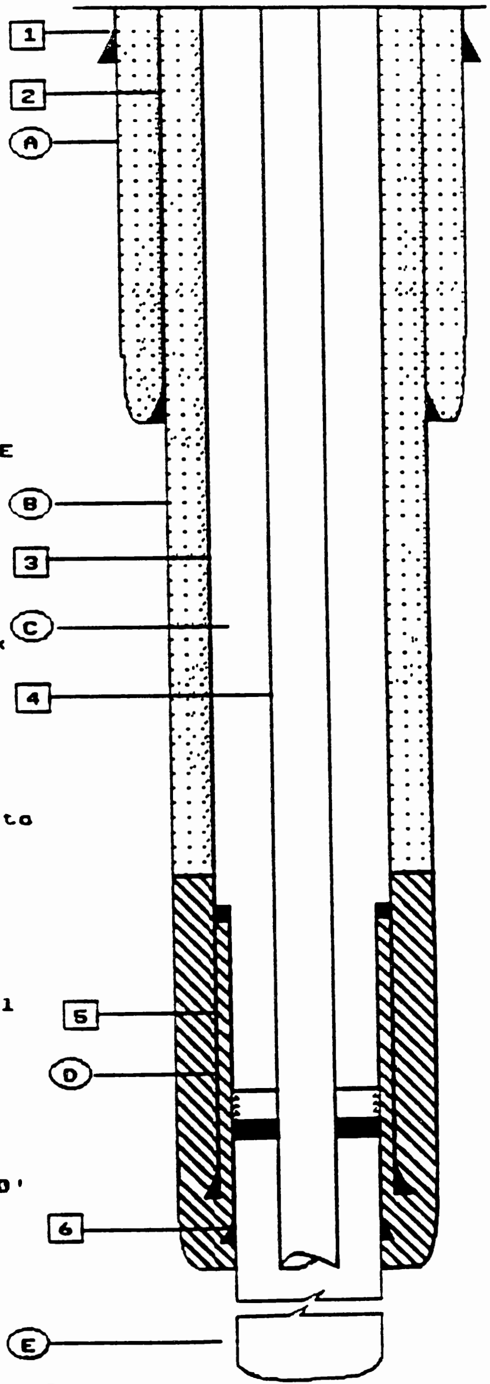

Figure 12. Well Schematic Well No. 2

TABLE 5

SUMMARY OF PROPERTIES FOR THE INJECTION WELLS

	(WPL1) WELL # 1	(WPL2) WELL # 2
Injection Zone Thickness (h) (ft)	1669	1795
Porosity (o)	0.15	0.15
Lateral Permeability (k) (md)	25.0	25.0
Injection Zone Compressibility (c) (psi)	$7.5\text{x}10^{-6}$	$7.5\text{x}10^{-6}$

TABLE 6

PROPERTIES OF INJECTED WASTES

	WELL # 1	WELL # 2
Viscosity (1) (CP)	1.2	1.2
Specific Gravity (1)	1.1	1.1
pH_o	0.8	0.8
pH_f	2.0	2.0
Concentration (2)	0.999	0.999

(1): At 75° F

(2): Determined from the relationship

$$10^{pH} = (C)\ 10^{pH_o} + (1-C)\ 10^{pH_F}$$

where:

pH_o = pH of injected fluid

pH_F = pH of formation fluid = 6.3

TABLE 7

HISTORICAL INJECTION VOLUMES

	WELL # 1		WELL # 2	
YEAR	GAL/YR.	STB/DAY	GAL/YR.	STB/DAY
65	NO		NO	
66	NO		NO	
67	NO		NO	
68	1.49xE7	848.01	NO	
69	2.56xE7	1669.90	NO	
70	2.35xE7	1532.94	NO	
71	1.49xE7	1298.10	NO	
72	2.32xE7	1513.39	NO	
73	2.75xE7	1793.80	NO	
74	2.47xE7	1932.37	NO	
75	1.64xE7	1069.80	NO	
76	3.64xE7	2374.42	NO	
77	3.83xE7	2498.36	NO	
78	2.85xE7	1859.07	NO	
79	3.35xE7	2185.25	NO	
80	2.32xE7	1513.37	NO	
81	4.81xE7	3137.63	NO	
82	5.42xE7	3535.50	NO	
83	8.98xE7	5857.70	NO	
84	7.97xE7	5198.90	6.0xE5	39.13
85	5.02xE7	3274.62	5.23xE7	3411.61
86	5.70xE7	3718.10	3.27xE7	2133.07
87(a)	1.54xE7	1004.56	4.04xE7	2635.35
TOTAL =	7.39xE8		1.26xE8	

a:AUG1987

TABLE 8

CONSTRUCTION DETAILS
(WELL # 1)

Total Depth	4300' +/-
Type of Completion	Open Hole
Open Hole Interval	2631' +/- - 4300'
Injection Tubing	3 1/2" Texas Fiberglass set at 2057' +/- 2 7/8" Texas Fiberglass set at 2057' +/- - 2631' +/-
Packer	4 1/2" Otis Interlock packer set to 2596' +/-
Casing Data	
Conductor	16", 65 lb/ft., H-40 set at 169' +/-
Surface	10 3/4", 32.75 lb/ft., H-40 set at 800' +/-
Long String	7", 26 lb/ft., J-55 set from 288' +/- to 2583' +/- 6 5/8" Fibercast set from 2283' +/- to 2583' +/- 5 1/2", 14 lb/ft., set at 2283'+/-
Liner	4 1/2" carbon steel & Hastelloy C276 liner from 2175' +/- 2631' +/-

All measurements from KB = 12' +/-

TABLE 9

CONSTRUCTION DETAILS
(WELL #2)

Total Depth	4385' +/-
Type of Completion	Open Hole
Open Hole Interval	2590' +/- - 4385' +/- (Epoxy resin cement estimated from 2590' to 2784' +/-)
Injection Tubing	4 1/2", 2000 psi, Texas Fiberglass set to 2582'+/-
Packer	6 /5/8" x 4 1/2" LOT Hastelloy C-276 set at 2520' +/-
Casing Data	
Conductor	20 " driven to 130'+/-
Surface Casing	13 3/8", 48 lb/ft., H-40 set at 810'+/-
Long String Casing	9 5/8", 36 lb/ft., J-55 set from surface tp 2495'+/- 8 5/8", Schedule 40 Hastelloy C from 2495'+/- to 2589'+/-
Liner	9 5/8" x 7" liner hanger w/ tieback assembly 2266'+/- to 2284'+/- 7", 32 lb/ft N-80 liner 2284'+/- to 2371'+/- 6 5/8" Sch 40 Hastelloy C-276 liner 2371'+/- to 2573'+/- 7" carbon steel cementing equipment 2557'+/- to 2573'+/-
Epoxy Resin Section	2557'+/- to 2784'+/- in 5 1/2" bore

All measurements from RB = 11'

APPENDIX C

CALCULATIONS AND RESULTS

Table 10

* LATERAL PRESSURE CALCULATION

$(r=0,\ t_D > 100)$

n	Well #1		Well #2		Multiple Well Effect	
	Q_n-Q_{n-1}		Q_n-Q_{n-1}		(Future 20yrs.)	
(yrs)	(STB/D)	P_{rn}(psi)	(STB/D)	P_{rn}(psi)	Q_{avg} ann	P_{r20} (psi)
20	848.01	34.20				
19	821.89	34.10				
18	-136.91	-5.68				
17	-234.89	-9.72				
16	215.29	8.89				
15	280.40	11.54				
14	143.57	5.89				
13	-867.57	-35.51				
12	1304.62	53.23				
11	123.94	5.04				
10	-639.35	-25.88				
9	326.24	13.15				
8	-671.88	26.95				
7	1624.26	64.79				
6	397.87	15.76				
5	2322.20	91.30				
4	-658.80	-25.65	39.13	1.35		
3	-1924.28	-73.99	3372.48	115.94		
2	443.48	16.75	-1278.57	-44.33		
1	-2713.54	-99.30	502.28	16.34	5072.40	239.16
P_{r20}		51.77		88.90		239.16

Total P_r = 379.83 psi

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* see chapter III, equations 11, 12, 13, and 14.

Table 11

*LATERAL PRESSURE CALCULATION

(r=2 miles, $t_D < 100$)

n	Well #1		Well #2		Multiple Well Effect	
	$Q_n - Q_{n-1}$		$Q_n - Q_{n-1}$		(Future 20yrs.)	
(yrs)	(STB/D)	P_{rn}(psi)	(STB/D)	P_{rn}(psi)	Q_{avg} ann	P_{r20} (psi)
20	848.01	4.1200				
19	821.89	3.9100				
18	-136.91	-0.6362				
17	-234.89	-1.0790				
16	215.29	0.9660				
15	280.40	1.2990				
14	143.57	0.6100				
13	-867.57	-3.5990				
12	1304.62	5.2600				
11	123.94	0.4400				
10	-639.35	-2.4000				
9	326.24	1.1680				
8	-671.88	-2.2970				
7	1624.26	5.1838				
6	397.87	1.1880				
5	2322.20	1.0640				
4	-658.80	-1.5690	39.13	0.0830		
3	-1924.28	-3.8770	3372.48	6.3290		
2	443.48	0.6323	-1278.57	-1.6900		
1	-2713.54	-1.8890	502.28	0.3240	5072.40	28.5300
P_{r20}		8.4200		5.0400		28.5300

Total P_r = 41.9900 psi

* see chapter III, equations 11, 12, 13, and 14.

Table 12

* LATERAL PRESSURE CALCULATION

(r=5 miles, $t_D < 100$)

n	Well #1		Well #2		Multiple Well Effect	
	Q_n-Q_{n-1}		Q_n-Q_{n-1}		(Future 20yrs.)	
(yrs)	(STB/D)	P_{rn}(psi)	(STB/D)	P_{rn}(psi)	$Q_{avg\ ann}$	P_{r20} (psi)
20	848.01	2.5400				
19	821.89	1.6200				
18	-136.91	-0.2570				
17	-234.89	-0.4270				
16	215.29	0.3720				
15	280.40	0.4668				
14	143.57	0.2260				
13	-867.57	-1.3200				
12	1304.62	1.8100				
11	123.94	0.1580				
10	-639.35	-0.7460				
9	326.24	0.3420				
8	-671.88	-0.6200				
7	1624.26	1.2900				
6	397.87	0.2600				
5	2322.20	1.2100				
4	-658.80	-0.2440	39.13	0.0130		
3	-1924.28	-0.3900	3372.48	0.6367		
2	443.48	0.0360	-1278.57	-0.0965		
1	-2713.54	-0.0156	502.28	0.0027	5072.40	17.6000
P_{r20}		3.7710		0.5559		17.6000

Total P_r = 22.0000 psi

* see chapter III, equations 11, 12, 13, and 14.

Table 13

* LATERAL PRESSURE CALCULATION

(r=8 miles, t_D < 100)

n	Well #1		Well #2		Multiple Well Effect	
	Q_n-Q_{n-1}		Q_n-Q_{n-1}		(Future 20yrs.)	
(yrs)	(STB/D)	P_{rn}(psi)	(STB/D)	P_{rn}(psi)	$Q_{avg\ ann}$	P_{r20} (psi)
20	848.01	0.7969				
19	821.89	0.7000				
18	-136.91	-0.1040				
17	-234.89	-0.1740				
16	215.29	0.1490				
15	280.40	0.1890				
14	143.57	0.0830				
13	-867.57	-0.3820				
12	1304.62	0.6070				
11	123.94	0.5800				
10	-639.35	-0.2270				
9	326.24	0.0090				
8	-671.88	-0.1540				
7	1624.26	0.3020				
6	397.87	0.0500				
5	2322.20	0.1920				
4	-658.80	-0.0243	39.13	0.0053		
3	-1924.28	-0.0227	3372.48	0.0413		
2	443.48	0.00067	-1278.57	-0.0181		
1	-2713.54	0.0000	502.28	0.0000	5072.40	7.9600
P_{r20}		2.6230		0.0285		7.9600

Total P_r = 10.6100 psi

* see chapter III, equations 11, 12, 13, and 14.

Table 14

* LATERAL PRESSURE CALCULATION

(r=10 miles, t_D < 100)

n	Well #1		Well #2		Multiple Well Effect	
	Q_n-Q_{n-1}		Q_n-Q_{n-1}		(Future 20yrs.)	
(yrs)	(STB/D)	P_{rn}(psi)	(STB/D)	P_{rn}(psi)	Q_{avg} ann	P_{r20} (psi)
20	848.01	0.4200				
19	821.89	0.3889				
18	-136.91	-0.0597				
17	-234.89	-0.0930				
16	215.29	0.0796				
15	280.40	0.09426				
14	143.57	0.0398				
13	-867.57	-0.2110				
12	1304.62	0.2730				
11	123.94	0.0226				
10	-639.35	-0.0864				
9	326.24	0.0353				
8	-671.88	-0.0498				
7	1624.26	0.0823				
6	397.87	0.0120				
5	2322.20	0.0373				
4	-658.80	-0.0040	39.13	0.00021		
3	-1924.28	-0.00227	3372.48	0.00371		
2	443.48	0.00000	-1278.57	-0.00000		
1	-2713.54	0.00000	502.28	0.00000	5072.40	2.9700
P_{r20}		0.9789		0.00392		2.9770

Total P_r = 3.9600 psi

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* see chapter III, equations 11, 12, 13, and 14.

Table 15

* LATERAL PRESSURE CALCULATION

(r=15 miles, t_D < 100)

n	Well #1		Well #2		Multiple Well Effect	
	Q_n-Q_{n-1}		Q_n-Q_{n-1}		(Future 20yrs.)	
(yrs)	(STB/D)	P_{rn}(psi)	(STB/D)	P_{rn}(psi)	Q_{avg} ann	P_{r20} (psi)
20	848.01	0.0860				
19	821.89	0.0870				
18	-136.91	0.0778				
17	-234.89	-0.00106				
16	215.29	-0.0155				
15	280.40	0.0000				
14	143.57	0.0110				
13	-867.57	0.0125				
12	1304.62	0.00485				
11	123.94	-0.0236				
10	-639.35	0.0264				
9	326.24	0.00171				
8	-671.88	0.00627				
7	1624.26	0.00198				
6	397.87	-0.00215				
5	2322.20	0.00247				
4	-658.80	0.00020	39.13	0.0000		
3	-1924.28	0.000392	3372.48	0.0000		
2	443.48	0.0000	-1278.57	-0.0000		
1	-2713.54	0.0000	502.28	0.0000	5072.40	0.6028
P_{r20}		0.1923		0.0000		0.6028

Total P_r = 0.7951 psi

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* see chapter III, equations 11, 12, 13, and 14.

APPENDIX D

TABLE FOR CONVERSION AND VALUES OF THE WELL FUNCTION

Table 16

CONVERSIONS

WEIGHT

Equivalents of First Column

Unit	Grams	Kilograms	Ounces (Avoir-dupois)	Pounds (Avoir-dupois)	Tons (Short)	Tons (Long)
1 Gram	1	001	.0353	.0022	.0000011	.00000098
1 Kilogram	1000	1	35.274	2.205	.0011	.000984
1 Ounce (Avoirdupois)	28.349	0283	1	.0625	.0000312	.0000279
1 Pound (Avoirdupois)	453.592	454	16	1	.0005	000446
1 Ton (Short)	907.184.8	907.185	32,000	2,000	1	.893
1 Ton (Long)	1,016,046.98	1,016.047	35,840	2,240	1.12	1

Gallons per Minute--Gallons per Day--Cubic Feet per Second

G.P M.*	G.P D.*	Sec. Ft *	G.P.D *	G.P M.*	Sec. Ft.*
10	14,400	0.022	10,000	6.9	0.015
20	28,800	0.045	20,000	13.9	0.031
30	43,200	0.067	30,000	20.8	0.045
40	57,600	0.089	40,000	27.8	0.062
50	72,000	0.111	50,000	34.7	0.077
75	108,000	0.167	75,000	52.1	0.116
100	144,000	0.223	100,000	69.4	0.155
125	180,000	0.279	120,000	83.3	0.186
150	216,000	0 334	140,000	97.2	0.217
175	252,000	0.390	160,000	111.1	0.248

Table 16 (Continued)

Gallons per Minute--Gallons per Day--Cubic Feet per Second

G.P M *	G.P D *	Sec. Ft *	G.P D *	G.P M.*	Sec. Ft.*
200	288,000	0.446	180,000	125.0	0.015
250	360,000	0.557	200,000	138.9	0.309
300	432,000	0.668	300,000	208.3	0.464
350	504,000	0.780	400,000	277.8	0.619
400	576,000	0.391	500,000	347.2	0.774
450	648,000	1.00	600,000	416.7	0.928
500	720,000	1 11	700,000	486.1	1.08
550	792,000	1.23	800,000	555.6	1.24
600	864,000	1 34	900,000	625.0	1.39
650	936,000	1 45	1,000,000	694.4	1.55
700	1,008,000	1 56	1,200,000	833.3	1.86
750	1,080,000	1 67	1,400,000	972.2	2.17
800	1,152,000	1 78	1,600,000	1111.1	2.48
850	1,224,000	1 89	1,800,000	1250.0	2.79
900	1,296,000	2.01	2,000,000	1368.9	3.09
950	1,368,000	2.12	2,500,000	1736.1	3.87
1000	1,440,000	2.23	3,000,000	2083.3	4.64
1200	1,728,000	2.67	3,500,000	2430.6	5.42
1400	2,016,000	3 12	4,000,000	2777.8	6.19
1600	2,304,000	3 57	4,500,000	3125.0	6.96
1800	2,592,000	4 01	5,000,000	3472.2	7.74
2000	2,880,000	4 46	10,000,000	6944.4	15.5

* - G.P.M.: U.S. Gallons per Minute
G.P.D.: U.S. Gallons per 24-Hour Day
Sec. Ft.: Cubic Feet per Second

Table # 17

COMPARISON OF UNITS IN PETROLEUM INDUSTRY WITH UNITS BY GROUNDWATER INDUSTRY

Ground-Water Industry Unit	Equivalent Petroleum Industry Unit
Gallon (gal.) (42 Gallons) 9,702 cu. inches 5.615 cu. feet.	1/42 Barrel (bbl.). . 1 Barrel
Q-gallons per minute (gpm)	34.29 Barrels per day (B/D)
Drawdown in feet (s) pumping level minus static water level (SWL) (s_a) - actual drawdown (s_t) - theoretical drawdown of 100% efficient well	Differential pressure = 0.433 psi/ft of drawdown for water with a specific gravity of 1.0
Specific capacity (S) gpm per foot of drawdown	Productivity index (P.I.) 79.91 B/D per psi
Permeability:	Permeability:
meinzer - gallons per day of water at 60°F per square foot at 100% hydraulic gradient	$\frac{1}{18.24}$ darcy - cubic centimeters per second per square centimeter at one dyne per square centimeter length and viscosity of one centipoise.
	54.82 millidarcy
18.24 gallons/day/sq. foot (60°F)	1 darcy
(0.01824 gals/day/sq. foot)	1 millidarcy
Transmissibility:	Transmissibility:
gpd - ft. at prevailing temperature at 100% hydraulic gradient	$\frac{1}{20.38}$ darcy-ft. per centipoise
	49.07 millidarcy-ft. per centipoise

TABLE 18

VALUES OF THE EXPONENTIAL INTEGRAL

Values of E(u)

	0.0	0.1000	0.2000	0.3000	0.4000	0.5000	0.6000	0.7000	0.8000	0.9000
POWER OF 10 = -16										
1	36.2642	36.1688	36.0818	36.0018	35.9277	35.8587	35.7941	35.7335	35.6764	35.6223
2	35.5710	35.5222	35.4757	35.4312	35.3887	35.3479	35.3086	35.2709	35.2345	35.1994
3	35.1655	35.1328	35.1010	35.0702	35.0404	35.0114	34.9832	34.9558	34.9292	34.9032
4	34.8779	34.8532	34.8291	34.8055	34.7825	34.7601	34.7381	34.7166	34.6955	34.6749
5	34.6547	34.6349	34.6155	34.5965	34.5778	34.5594	34.5414	34.5237	34.5063	34.4892
6	34.4724	34.4559	34.4396	34.4236	34.4079	34.3923	34.3771	34.3620	34.3472	34.3326
7	34.3182	34.3041	34.2901	34.2763	34.2627	34.2493	34.2360	34.2229	34.2100	34.1973
8	34.1847	34.1723	34.1600	34.1479	34.1359	34.1241	34.1124	34.1008	34.0894	34.0781
9	34.0669	34.0559	34.0450	34.0341	34.0234	34.0129	34.0024	33.9920	33.9818	33.9716
POWER OF 10 = -15										
1	33.9616	33.8663	33.7793	33.6992	33.6251	33.5561	33.4916	33.4309	33.3738	33.3197
2	33.2684	33.2196	33.1731	33.1287	33.0861	33.0453	33.0061	32.9683	32.9319	32.8969
3	32.8630	32.8302	32.7984	32.7676	32.7378	32.7088	32.6806	32.6532	32.6266	32.6006
4	32.5753	32.5506	32.5265	32.5030	32.4800	32.4575	32.4355	32.4140	32.3930	32.3723
5	32.3521	32.3323	32.3129	32.2939	32.2752	32.2568	32.2388	32.2211	32.2037	32.1866
6	32.1698	32.1533	32.1370	32.1210	32.1053	32.0898	32.0745	32.0595	32.0446	32.0300
7	32.0157	32.0015	31.9875	31.9737	31.9601	31.9467	31.9334	31.9203	31.9074	31.8947
8	31.8821	31.8697	31.8574	31.8453	31.8333	31.8215	31.8098	31.7982	31.7868	31.7755
9	31.7643	31.7533	31.7424	31.7316	31.7209	31.7103	31.6998	31.6894	31.6792	31.6690
POWER OF 10 = -14										
1	31.6590	31.5637	31.4767	31.3966	31.3225	31.2535	31.1890	31.1284	31.0712	31.0171
2	30.9658	30.9171	30.8705	30.8261	30.7835	30.7427	30.7035	30.6657	30.6294	30.5943
3	30.5604	30.5276	30.4958	30.4651	30.4352	30.4062	30.3781	30.3506	30.3240	30.2980
4	30.2727	30.2480	30.2239	30.2004	30.1774	30.1549	30.1329	30.1114	30.0904	30.0697
5	30.0495	30.0297	30.0103	29.9913	29.9726	29.9542	29.9362	29.9185	29.9011	29.8840
6	29.8672	29.8507	29.8344	29.8184	29.8027	29.7872	29.7719	29.7569	29.7421	29.7275
7	29.7131	29.6989	29.6849	29.6711	29.6575	29.6441	29.6308	29.6178	29.6049	29.5921
8	29.5795	29.5671	29.5549	29.5427	29.5307	29.5189	29.5072	29.4957	29.4842	29.4729
9	29.4618	29.4507	29.4398	29.4290	29.4183	29.4077	29.3972	29.3869	29.3766	29.3665
POWER OF 10 = -13										
1	29.3564	29.2611	29.1741	29.0940	29.0199	28.9509	28.8864	28.8258	28.7686	28.7145
2	28.6633	28.6145	28.5679	28.5235	28.4809	28.4401	28.4009	28.3631	28.3268	28.2917
3	28.2578	28.2250	28.1933	28.1625	28.1326	28.1036	28.0755	28.0481	28.0214	27.9954
4	27.9701	27.9454	27.9213	27.8978	27.8748	27.8523	27.8303	27.8088	27.7876	27.7672
5	27.7470	27.7272	27.7077	27.6887	27.6700	27.6517	27.6336	27.6159	27.5985	27.5815
6	27.5646	27.5481	27.5318	27.5159	27.5001	27.4846	27.4693	27.4543	27.4395	27.4249
7	27.4105	27.3963	27.3823	27.3685	27.3549	27.3415	27.3282	27.3152	27.3023	27.2895
8	27.2770	27.2645	27.2523	27.2401	27.2282	27.2163	27.2046	27.1931	27.1816	27.1703
9	27.1592	27.1481	27.1372	27.1264	27.1157	27.1051	27.0946	27.0843	27.0740	27.0639

TABLE 18 (Continued)

Values of E(u)

	0.0	0.1000	0.2000	0.3000	0.4000	0.5000	0.6000	0.7000	0.8000	0.9000
POWER OF 10 = -12										
1	27.0538	26.9585	26.8715	26.7915	26.7173	26.6483	26.5838	26.5232	26.4660	26.4120
2	26.3607	26.3119	26.2654	26.2209	26.1783	26.1375	26.0983	26.0606	26.0242	25.9891
3	25.9552	25.9224	25.8907	25.8599	25.8300	25.8011	25.7729	25.7455	25.7188	25.6928
4	25.6675	25.6428	25.6187	25.5952	25.5722	25.5497	25.5278	25.5063	25.4852	25.4646
5	25.4444	25.4246	25.4052	25.3861	25.3674	25.3491	25.3311	25.3134	25.2960	25.2789
6	25.2621	25.2455	25.2293	25.2133	25.1975	25.1820	25.1667	25.1517	25.1369	25.1223
7	25.1079	25.0937	25.0797	25.0659	25.0523	25.0389	25.0257	25.0126	24.9997	24.9870
8	24.9744	24.9619	24.9497	24.9376	24.9256	24.9137	24.9021	24.8905	24.8791	24.8678
9	24.8566	24.8455	24.8346	24.8238	24.8131	24.8025	24.7921	24.7817	24.7714	24.7613
POWER OF 10 = -11										
1	24.7512	24.6559	24.5689	24.4889	24.4147	24.3458	24.2812	24.2206	24.1634	24.1094
2	24.0581	24.0093	23.9628	23.9183	23.8758	23.8349	23.7957	23.7580	23.7216	23.6865
3	23.6526	23.6198	23.5881	23.5573	23.5275	23.4985	23.4703	23.4429	23.4162	23.3903
4	23.3649	23.3402	23.3161	23.2926	23.2696	23.2471	23.2252	23.2037	23.1826	23.1620
5	23.1418	23.1220	23.1026	23.0835	23.0648	23.0465	23.0285	23.0108	22.9934	22.9763
6	22.9595	22.9429	22.9267	22.9107	22.8949	22.8794	22.8642	22.8491	22.8343	22.8197
7	22.8053	22.7911	22.7771	22.7634	22.7497	22.7363	22.7231	22.7100	22.6971	22.6844
8	22.6718	22.6594	22.6471	22.6350	22.6230	22.6112	22.5995	22.5879	22.5765	22.5652
9	22.5540	22.5430	22.5320	22.5212	22.5105	22.4999	22.4895	22.4791	22.4688	22.4587
POWER OF 10 = -10										
1	22.4486	22.3533	22.2663	22.1863	22.1122	22.0432	21.9786	21.9180	21.8609	21.8068
2	21.7555	21.7067	21.6602	21.6157	21.5732	21.5323	21.4931	21.4554	21.4190	21.3839
3	21.3500	21.3172	21.2855	21.2547	21.2249	21.1959	21.1677	21.1403	21.1136	21.0877
4	21.0623	21.0377	21.0136	20.9900	20.9670	20.9446	20.9226	20.9011	20.8800	20.8594
5	20.8392	20.8194	20.8000	20.7809	20.7622	20.7439	20.7259	20.7082	20.6908	20.6737
6	20.6569	20.6404	20.6241	20.6081	20.5923	20.5768	20.5616	20.5465	20.5317	20.5171
7	20.5027	20.4886	20.4746	20.4608	20.4472	20.4337	20.4205	20.4074	20.3945	20.3816
8	20.3692	20.3568	20.3445	20.3324	20.3204	20.3086	20.2969	20.2853	20.2739	20.2626
9	20.2514	20.2404	20.2294	20.2186	20.2079	20.1974	20.1869	20.1765	20.1663	20.1561
POWER OF 10 = -9										
1	20.1461	20.0508	19.9637	19.8837	19.8096	19.7406	19.6761	19.6154	19.5583	19.5042
2	19.4529	19.4041	19.3576	19.3132	19.2706	19.2298	19.1906	19.1528	19.1164	19.0813
3	19.0474	19.0147	18.9829	18.9521	18.9223	18.8933	18.8651	18.8377	18.8111	18.7851
4	18.7598	18.7351	18.7110	18.6874	18.6645	18.6420	18.6200	18.5985	18.5774	18.5568
5	18.5366	18.5168	18.4974	18.4783	18.4597	18.4413	18.4233	18.4056	18.3882	18.3711
6	18.3543	18.3378	18.3215	18.3055	18.2898	18.2743	18.2590	18.2440	18.2291	18.2145
7	18.2001	19.1860	18.1720	18.1582	18.1446	18.1311	18.1179	18.1048	18.0919	18.0792
8	18.0666	18.0542	18.0419	18.0298	18.0178	18.0060	17.9943	17.9827	17.9713	17.9600
9	17.9488	17.9378	17.9268	17.9160	17.9053	17.8948	17.8843	17.8739	17.8637	17.8535

TABLE 18 (Continued)

Values of E(u)

POWER OF 10 = -8

	0.0	0.1000	0.2000	0.3000	0.4000	0.5000	0.6000	0.7000	0.8000	0.9000
1	17.8435	17.7482	17.6611	17.5811	17.5070	17.4380	17.3735	17.3129	17.2557	17.2016
2	17.1503	17.1015	17.0550	17.0106	16.9680	16.9272	16.8880	16.8502	16.8139	16.7788
3	16.7449	16.7121	16.6803	16.6496	16.6197	16.5907	16.5625	16.5351	16.5085	16.4825
4	16.4572	16.4325	16.4084	16.3849	16.3619	16.3394	16.3174	16.2959	16.2749	16.2542
5	16.2340	16.2142	16.1948	16.1758	16.1571	16.1387	16.1207	16.1030	16.0856	16.0685
6	16.0517	16.0352	16.0189	16.0029	15.9872	15.9717	15.9564	15.9414	15.9266	15.9120
7	15.8976	15.8834	15.8694	15.8556	15.8420	15.8286	15.8153	15.8023	15.7894	15.7766
8	15.7640	15.7516	15.7393	15.7272	15.7152	15.7034	15.6917	15.6802	15.6687	15.6574
9	15.6463	15.6352	15.6243	15.6135	15.6028	15.5922	15.5817	15.5714	15.5611	15.5509

POWER OF 10 = -7

	0.0	0.1000	0.2000	0.3000	0.4000	0.5000	0.6000	0.7000	0.8000	0.9000
1	15.5409	15.4456	15.3586	15.2785	15.2044	15.1354	15.0709	15.0103	14.9531	14.8990
2	14.8477	14.7990	14.7524	14.7080	14.6654	14.6246	14.5854	14.5476	14.5113	14.4762
3	14.4423	14.4095	14.3777	14.3470	14.3171	14.2881	14.2600	14.2326	14.2059	14.1799
4	14.1546	14.1299	14.1058	14.0823	14.0593	14.0368	14.0148	13.9933	13.9723	13.9517
5	13.9315	13.9117	13.8922	13.8732	13.8545	13.8361	13.8181	13.8004	13.7830	13.7659
6	13.7491	13.7326	13.7163	13.7003	13.6846	13.6691	13.6538	13.6388	13.6240	13.6094
7	13.5950	13.5808	13.5668	13.5530	13.5394	13.5260	13.5127	13.4997	13.4868	13.4740
8	13.4615	13.4490	13.4368	13.4246	13.4127	13.4008	13.3891	13.3776	13.3661	13.3548
9	13.3437	13.3326	13.3217	13.3109	13.3002	13.2896	13.2791	13.2688	13.2585	13.2484

POWER OF 10 = -6

	0.0	0.1000	0.2000	0.3000	0.4000	0.5000	0.6000	0.7000	0.8000	0.9000
1	13.2383	13.1430	13.0560	12.9759	12.9018	12.8328	12.7683	12.7077	12.6505	12.5965
2	12.5452	12.4964	12.4499	12.4054	12.3628	12.3220	12.2828	12.2451	12.2087	12.1736
3	12.1397	12.1069	12.0752	12.0444	12.0145	11.9856	11.9574	11.9300	11.9033	11.8773
4	11.8520	11.8273	11.8032	11.7797	11.7567	11.7342	11.7123	11.6908	11.6697	11.6491
5	11.6289	11.6091	11.5897	11.5706	11.5519	11.5336	11.5155	11.4979	11.4805	11.4634
6	11.4466	11.4300	11.4138	11.3978	11.3820	11.3665	11.3512	11.3362	11.3214	11.3068
7	11.2924	11.2782	11.2642	11.2504	11.2368	11.2234	11.2102	11.1971	11.1842	11.1715
8	11.1589	11.1465	11.1342	11.1221	11.1101	11.0983	11.0866	11.0750	11.0636	11.0523
9	11.0411	11.0300	11.0191	11.0083	10.9976	10.9870	10.9766	10.9662	10.9559	10.9458

POWER OF 10 = -5

	0.0	0.1000	0.2000	0.3000	0.4000	0.5000	0.6000	0.7000	0.8000	0.9000
1	10.9357	10.8404	10.7534	10.6734	10.5993	10.5303	10.4657	10.4051	10.3480	10.2939
2	10.2426	10.1939	10.1473	10.1028	10.0603	10.0195	9.9802	9.9425	9.9061	9.8710
3	9.8371	9.8044	9.7726	9.7418	9.7120	9.6830	9.6548	9.6274	9.6008	9.5748
4	9.5495	9.5248	9.5007	9.4772	9.4542	9.4317	9.4097	9.3882	9.3672	9.3465
5	9.3263	9.3065	9.2871	9.2681	9.2494	9.2310	9.2130	9.1953	9.1779	9.1608
6	9.1440	9.1275	9.1112	9.0952	9.0795	9.0640	9.0487	9.0337	9.0189	9.0043
7	8.9899	8.9757	8.9617	8.9479	8.9343	8.9209	8.9077	8.8946	8.8817	8.8689
8	8.8564	8.8439	8.8317	8.8196	8.8076	8.7957	8.7840	8.7725	8.7611	8.7498
9	8.7386	8.7275	8.7166	8.7058	8.6951	8.6845	8.6741	8.6637	8.6534	8.6433

TABLE 18 (Continued)

Values of E(u)

	0.0	0.1000	0.2000	0.3000	0.4000	0.5000	0.6000	0.7000	0.8000	0.9000
					POWER OF 10 =	-4				
1	8.6332	8.5379	8.4509	8.3709	8.2968	8.2278	8.1633	8.1027	8.0455	7.9915
2	7.9402	7.8914	7.8449	7.8005	7.7579	7.7171	7.6779	7.6402	7.6038	7.5687
3	7.5348	7.5020	7.4703	7.4395	7.4097	7.3807	7.3526	7.3252	7.2985	7.2726
4	7.2472	7.2226	7.1985	7.1750	7.1520	7.1295	7.1075	7.0860	7.0650	7.0444
5	7.0242	7.0044	6.9850	6.9660	6.9473	6.9289	6.9109	6.8932	6.8759	6.8588
6	6.8420	6.8255	6.8092	6.7932	6.7775	6.7620	6.7467	6.7317	6.7169	6.7023
7	6.6879	6.6738	6.6598	6.6460	6.6324	6.6190	6.6058	6.5927	6.5798	6.5671
8	6.5545	6.5421	6.5298	6.5177	6.5057	6.4939	6.4822	6.4707	6.4593	6.4480
9	6.4368	6.4258	6.4149	6.4041	6.3934	6.3828	6.3723	6.3620	6.3517	6.3416
					POWER OF 10 =	-3				
1	6.3316	6.2363	6.1494	6.0695	5.9955	5.9266	5.8622	5.8016	5.7446	5.6906
2	5.6394	5.5907	5.5443	5.4999	5.4575	5.4168	5.3776	5.3400	5.3037	5.2687
3	5.2349	5.2023	5.1706	5.1399	5.1102	5.0813	5.0532	5.0259	4.9994	4.9735
4	4.9483	4.9237	4.8997	4.8762	4.8533	4.8310	4.8091	4.7877	4.7667	4.7462
5	4.7261	4.7064	4.6871	4.6681	4.6495	4.6313	4.6134	4.5958	4.5785	4.5615
6	4.5448	4.5284	4.5122	4.4963	4.4806	4.4652	4.4501	4.4351	4.4204	4.4059
7	4.3916	4.3775	4.3637	4.3500	4.3365	4.3231	4.3100	4.2970	4.2842	4.2716
8	4.2591	4.2468	4.2346	4.2226	4.2107	4.1990	4.1874	4.1759	4.1646	4.1534
9	4.1423	4.1314	4.1205	4.1098	4.0992	4.0887	4.0784	4.0681	4.0579	4.0479
					POWER OF 10 =	-2				
1	4.0379	3.9436	3.8576	3.7786	3.7054	3.6374	3.5739	3.5143	3.4581	3.4050
2	3.3547	3.3069	3.2614	3.2179	3.1764	3.1365	3.0983	3.0615	3.0262	2.9921
3	2.9591	2.9273	2.8966	2.8668	2.8379	2.8099	2.7827	2.7563	2.7306	2.7056
4	2.6813	2.6576	2.6344	2.6119	2.5899	2.5684	2.5474	2.5269	2.5068	2.4871
5	2.4679	2.4491	2.4306	2.4126	2.3949	2.3775	2.3604	2.3437	2.3273	2.3112
6	2.2953	2.2798	2.2645	2.2494	2.2347	2.2201	2.2058	2.1918	2.1779	2.1643
7	2.1509	2.1376	2.1246	2.1118	2.0991	2.0867	2.0744	2.0623	2.0504	2.0386
8	2.0270	2.0155	2.0042	1.9930	1.9820	1.9711	1.9604	1.9498	1.9393	1.9290
9	1.9188	1.9087	1.8987	1.8888	1.8791	1.8695	1.8600	1.8505	1.8412	1.8320
					POWER OF 10 =	-1				
1	1.8229	1.7371	1.6596	1.5889	1.5242	1.4645	1.4092	1.3578	1.3098	1.2649
2	1.2227	1.1829	1.1454	1.1099	1.0763	1.0443	1.0139	0.9849	0.9573	0.9309
3	0.9057	0.8815	0.8584	0.8361	0.8148	0.7942	0.7745	0.7555	0.7371	0.7195
4	0.7024	0.6859	0.6700	0.6546	0.6397	0.6253	0.6114	0.5979	0.5848	0.5721
5	0.5598	0.5478	0.5362	0.5250	0.5140	0.5034	0.4930	0.4830	0.4732	0.4637
6	0.4544	0.4454	0.4366	0.4280	0.4197	0.4115	0.4036	0.3959	0.3883	0.3810
7	0.3738	0.3668	0.3599	0.3533	0.3467	0.3404	0.3341	0.3280	0.3221	0.3163
8	0.3106	0.3051	0.2996	0.2943	0.2891	0.2840	0.2791	0.2742	0.2694	0.2648
9	0.2602	0.2557	0.2513	0.2470	0.2428	0.2387	0.2347	0.2308	0.2269	0.2231

VITA

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Master of Science

Thesis: COMPARISON OF PRESSURE BUILDUP IN INJECTION WELLS USING ANALYTICAL AND NUMERICAL MODELS

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